

HANDBOOK OF RESEARCH ON

Solar Energy Systems and Technologies



Sohail Anwar, Harry Efstathiadis & Salahuddin Qazi

Handbook of Research on Solar Energy Systems and Technologies

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Radian Belu, Drexel University, USA & Desert Research Institute, USA

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Tugrul U Daim, Portland State University, USA

Paul R. Newman, Portland State University, USA

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As Saudi Arabia is going through a significant economic and technological development, the country needs additional electric power generation to sustain the economic growth. Fossil fuels, however, are not sustainable as they are subject to eventful depletion. This chapter provides an examination of power generation alternatives for Saudi Arabia. Since the country is blessed with an abundant solar flux throughout the year, the construction of solar powered electrical generation plants in Saudi Arabia is proposed. However, due to the availability of different solar technologies, it is important to determine the optimal technology. In this chapter, a mathematical model called Hierarchical Decision Model (HDM) is used to make the technology selection.

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Sohail Anwar, Pennsylvania State University – Altoona College, USA

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Given the expanding use of solar energy, there is a need to educate society about solar energy. Thus, solar energy education and training programs should be developed at different educational levels to fulfill this need. Such programs need to recognize the environmental value of solar energy and the life cycle advantages of solar energy systems. This chapter provides an overview of the status of solar energy education and training in the United States. Though the focus of this chapter is on the solar energy education and training programs provided by the academic institutions in the USA, a short description of non-academic programs is also provided.

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Sohail Anwar, Pennsylvania State University – Altoona College, USA

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This chapter describes a project-based international collaboration in renewable energy systems design and implementation. The collaboration involves several educational institutions in Europe and USA. Working in teams, the undergraduate students at the partner institutions gain valuable experience in renewable energy systems design and construction. The participating students also learn effective teamwork and project management skills.

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Preface

Solar energy refers to the energy collected directly from sunlight. Solar power is the conversion of sunlight into electricity, referred to as photovoltaics. Photovoltaic systems are already an important part of our lives, powering many of the small calculators and wrist watches we use every day.

Over the last few decades, the developments in solar energy applications have made it possible to use solar energy for most of our energy needs. At present, solar energy applications are well developed for heating and cooling of buildings, electricity production for stationary and mobile applications, and for environmental cleanup.

Solar technologies are broadly categorized as either passive or active, depending on how they capture, convert, and distribute sunlight. Passive solar technologies involve selection of materials with favorable thermal properties, designing spaces that naturally circulate air, and referencing the position of building the sun. Active solar technologies make use of photovoltaic panels, pumps, and fans to convert sunlight into useful outputs.

Some of the advantages of solar energy are:

- Solar power can be used in both large-scale applications and in smaller systems for homes.
- Business and industry can diversify their energy sources, improve efficiency, and save money by choosing solar technologies for heating and cooling, industrial processes, electricity, and water heating.
- Homeowners can use solar technologies for heating, cooling, and water heating, and these technologies may produce enough electricity to operate “off-grid” or sell the extra electricity to the utilities, depending on local programs.
- The use of solar heating and daylighting design strategies can help both homes and commercial buildings operate more efficiently.

The scientific stage is set for rapid progress in solar energy research. There have been advances in nanoscience and nanotechnology, allowing unprecedented manipulation of the nanoscale structures, controlling solar capture, conversion, and storage. Light interacts with materials on the scale of its wavelength, a few hundred nanometers. Energy capture occurs via excited electron states confined by defect structures or interfaces to dimensions of tens of nanometers. Conversion of excited electrons to fuels such as ethanol, methane, or hydrogen occurs in chemical reactions at the scale of molecules. These nanoscale processes have never been more accessible to observation and manipulation.

The Handbook of Research on Solar Energy Systems and Technologies, which is divided into 20 chapters, addresses the research priorities in the topical area of solar energy. The Handbook provides up-to-date and relevant information regarding current and future research in:

- Photovoltaic Devices (polycrystalline thin film photovoltaics; nanocrystalline silicon solar cells, non-silicon based photovoltaics; CdTe based solar cells; polymer based solar cells; tandem solar cells and third generation solar cells).
- Nanostructures for solar energy conversion
- Solar energy conversion materials
- Solar energy storage
- The economics of solar energy
- Application of nanotechnology innovations to solar energy technologies

Chapter 1 focuses on the control and conversion of solar energy. The conversion of solar energy into thermal and electrical energy constitutes a key topical area for renewable energy. Solar electric systems find applications in rural electricity generation, water pumping, and satellite communications. Solar power is harvested and stored by charging rechargeable batteries. This chapter describes design and implementation of a solar battery charger using a single ended primary inductance converter (SEPIC).

Chapter 2 presents coverage of different methods and technologies used for the solar thermal storage in the terrestrial and space applications. The performance enhancement of these technologies using nanotechnology is also described. Moreover, this chapter provides coverage of various economic and environmental feasibility studies focusing on the storage of solar energy. Recommendations are made for developing new methods and enhancing the performance of existing techniques used to store solar energy.

In the case of solar energy, it is shown that optimal energy is obtained when the rays of the sun are incident normally on the collecting surface. Therefore, several techniques and experiments have been conducted recently to develop efficient solar tracking systems. Solar panel tracking systems optimize energy output of photovoltaic panels by positioning them to follow the sun's path throughout the day. The sun's position in the sky varies both with installation location, the seasons, and the time of day. Currently, most solar panels have fixed orientation to the sky and do not turn to follow the sun. To increase the unit area illumination of sunlight on solar panels, the design of a solar tracking electricity generation system is described in Chapter 3. The design mechanism holds the solar panel and allows the panel to track the sun's movement during the day and improve the overall electricity generation. This system can achieve the maximum illumination and energy concentration and cut the cost of electricity by requiring fewer solar panels. An electro-optical control unit tracks the sun by a solar detecting device that is sensitive to solar radiance. The simulation is experimental results verifying the effectiveness of the light tracking solar system is presented in this chapter.

The photovoltaic (PV) systems extensively use advanced power electronics technologies. Power electronics provides a useful means of efficiency improvement in the photovoltaic and the solar-thermal energy systems. Furthermore, the use of appropriate power electronics enables solar generated electricity to be integrated into power grid. Chapter 4 provides a detailed description of the current advances in power electronics that enable the photovoltaic systems to become a real power source for the power utility grid and for many stand-alone applications. The future developments in power electronics and controls that are expected to lead to more efficient solar energy systems and devices are also discussed in this chapter.

Currently, there is a significant research interest in third generation thin-film solar cells such as all-silicon tandem solar cells and multi-junction solar cells targeting substantial improvements in energy conversion efficiency leading to a reduction in the overall power costs. The semiconductor bandgap can be controlled by quantum-confinement of carriers in small quantum-dots dispersed in an amorphous matrix of silicon oxide, nitride, and polymer materials. Cells based on “hot” carriers are also of great interest since they offer the potential for very high efficiency from simple device structures. Chapter 5 provides a detailed account of the first, second, and the third generation of solar cells.

It has been shown that the use of nanotechnology in the form of quantum dots, nanorods, and nanotubes, results in an enhancement of absorption of sunlight and an increase in the efficiency of photovoltaic cells. Chapter 6 provides a comprehensive coverage of the nanotechnology applications in photovoltaic systems. The chapter describes the use of nanotechnology in the implementation of low cost, highly efficient, and easy to implement photovoltaic cells. Future research directions are also discussed in this chapter.

Chapter 7 focuses on Copper Indium Gallium Selenide (CIGS) and the nanocrystalline silicon solar cells. Heterojunctions based on CIGS have been studied for several years, and have shown very stable performance in field tests. The chapter covers various preparation methods for CIGS solar cells, the effects of composition ratio on the performance, doping profiles, alternative buffer layers, low cost fabrication techniques, as well as global market trends. Nanocrystalline silicon films have also recently attracted attention for use in photovoltaic solar cells as they provide an approach which results in lower cost and higher efficiency than conventional solar cells. Furthermore, silicon based nanoparticles or superlattices may be integrated with other materials for bandgap-engineered devices. Designed appropriately, variation of the effective bandgap across the device allows a larger portion of the solar spectrum to be coupled into the solar cell increasing the conversion efficiency.

Surface plasmons are oscillations of electrons arising from surface effects of light interaction with materials having significant free carrier densities. Surface plasmons have been recently utilized in a variety of methods used to increase the efficiency of solar cells. Research on silicon-based plasmonic solar cells has made use of the high scattering cross sections and favorable angular distributions of noble metal nanoparticle-scattered radiation to increase absorption of thin silicon devices. Chapter 8 focuses on the surface plasmon-enhanced thin film silicon solar cells. The chapter provides a comprehensive description of the current research related to these cells.

Polymer solar cells are cheaper to produce than conventional inorganic solar cells and can be processed at relatively low temperatures. The polymer solar cells can be fabricated on surfaces of arbitrary shape and flexibility. Therefore, polymer solar cells are likely to play an important role in addressing, at least in some small part, future energy needs. Chapter 9 provides coverage of the physics of polymer solar cells with a special emphasis on the computational tools. Two computer simulation models discussed in this chapter include the drift diffusion model and the Monte Carlo model.

Solar cells made from III-V materials are expensive, but outperform other solar cells. The polycrystalline III-V thin film solar cells on dissimilar substrates such as metal or glass can provide a low-cost venue for photovoltaic solar energy. The highly developed technology base of III-V semiconductors should favor this approach. Chapter 10 provides a detailed account of III-V solar cells. Different approaches for development of III-V solar cells are analyzed and compared with each other. The future prospects for low-cost III-V compound solar cells are also discussed in this chapter.

Chapter 11 provides an overview of the analytical techniques used for solar cells material characterization. The advantages and disadvantages of such techniques are compared. Most of these materials characterization techniques are based on the same principle, that is, an incident beam of photons or

charged particles interacting with specimen resulting in various types of signals. An appropriate detection system is used to collect these signals, and then the data are analyzed to gain information regarding the material properties being studied. The analytical techniques described in this chapter are categorized as imaging, compositional analysis, and the structural analysis methods.

Chapter 12 provides description of a mechatronic real-time solar tracker. The tracking array for the solar cell is pivoted on two axes using stepper motors to reflect the effects of daily and seasonal trajectories of the sun. The solar tracker described in this chapter is an example of the application of mechatronics in the discipline of renewable energy. The chapter content provides details regarding the design, programming, and the prototyping of this solar tracking system.

Computer simulations are commonly used for analyzing solar energy systems. The interaction of light with matter at a nanoscale level provides useful information regarding the structured and dynamical properties of photonic devices. The use of computer simulations will continue to increase as the researchers and developers face the challenges associated with the design and development of new devices and systems. Although Chapter 13 focuses on the development and application of the Finite Difference Time-Domain method to solar energy systems, it provides an overview of the new computational models covering the latest developments in nanophotonics technologies. The key improvements in the numeric solvers and new usability features are also described in this chapter.

Image processing is extensively utilized in solar cell research, device development, process control, and quality assurance. The use of solar image processing is expanding due to performance enhancement of commercial CCD and infrared cameras. Chapter 14 provides a comprehensive description of the key solar image processing methods and their applications. However, the emphasis of this chapter is on monocrystalline and polycrystalline silicon solar cells using infrared and visible wavelengths.

Artificial intelligence (AI) techniques are of significant importance in modeling, analysis, and prediction of the performance of renewable energy systems. Chapter 15 provides a comprehensive coverage of the commonly used artificial intelligence (AI) techniques in solar energy. The chapter places an emphasis on neural networks, fuzzy logic, and genetic algorithms. Selected AI applications in solar energy are also described in this chapter. Instead of complex rules and mathematical routines, AI techniques are able to learn the key information patterns within a multidimensional information domain. Design, control, and operation of solar energy systems require long-term series of meteorological data such as solar radiation, temperature or wind data. Such long-term measurements are often non-existent for most of the interest locations or, wherever they are available, they suffer of a number of shortcomings (e.g. poor quality of data, insufficient long series, etc.). To overcome these problems, AI techniques appear to be one of the strongest candidates.

Chapter 16 provides a detailed account of the time series and neural network methodologies used for solar radiation forecasting. The time series methodologies described in this chapter include autoregressive (AR), moving average (MA), autoregressive moving average (ARMA), and autoregressive integrated moving average (AIMA). The chapter also presents a detailed comparison of the solar radiation forecasting techniques. The advantages and disadvantages of using the neural network approach for solar radiation forecasting are outlined in this chapter.

Chapter 17 provides a description of the different solar thermal applications of greenhouse structure. Greenhouse structures are used to provide the ideal conditions required for the growth of agricultural crops throughout the year. Topics covered in the chapter include an introduction to the concept and importance of greenhouse technology, solar thermal applications in different greenhouse systems, and the use of photovoltaic systems for greenhouse drying. In this chapter, there is a special emphasis on greenhouse fish pond system design and working principles.

As Saudi Arabia is going through a significant economic and technological development, the country needs additional electric power generation to sustain the economic growth. Fossil fuels, however, are not sustainable as they are subject to eventful depletion. Chapter 18 provides an examination of power generation alternatives for Saudi Arabia. Since the country is blessed with an abundant solar flux throughout the year, the construction of solar powered electrical generation plants in Saudi Arabia is proposed. However, due to the availability of different solar technologies, it is important to determine the optimal technology. In this chapter, a mathematical model called Hierarchical Decision Model (HDM) is used to make the technology selection.

Given the expanding use of solar energy, there is a need to educate society about solar energy. Thus, solar energy education and training programs should be developed at different educational levels to fulfill this need. Such programs need to recognize the environmental value of solar energy and the life cycle advantages of solar energy systems. Chapter 19 provides an overview of the status of solar energy education and training in the United States. Though the focus of this chapter is on the solar energy education and training programs provided by the academic institutions in the USA, a short description of non-academic programs is also provided.

Chapter 20 describes a project-based international collaboration in renewable energy systems design and implementation. The collaboration involves several educational institutions in Europe and USA. Working in teams, the undergraduate students at the partner institutions gain valuable experience in renewable energy systems design and construction. The participating students also learn effective teamwork and project management skills.

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Chapter 1

Control and Conversion of Solar Power

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ABSTRACT

Solar energy conversion is one of the most addressed topics in the field of renewable energy. Solar radiation is usually converted into two forms of energy: thermal and electrical energy. Solar electricity has applications in many systems such as rural electricity, water pumping, and satellite communications. A solar power system consists of solar panels, dc-dc converters, controller, and load. Charging a rechargeable battery requires a regulated dc voltage. However, the voltage supplied by a solar panel can vary significantly depending upon the day, time, weather condition, and irradiation from the sun. Since solar power is unregulated, it cannot be supplied to the load directly. Solar power is harvested and stored by charging rechargeable batteries. A dc-dc converter is connected between the solar panel and the battery to charge the battery with a regulated voltage. Therefore, solar power can be properly converted and controlled to provide required electrical power to the load, and excessive power can be sent back to the electrical grid.

INTRODUCTION

In this chapter, the most recent development of digital power management and battery charging control will be introduced. Dc-dc converters convert unregulated input voltage into regulated output voltage. Digital PID (proportional-integral-derivative) type controllers can be applied to dc-dc converters for voltage regulation. Linear

PID controllers for dc-dc converters are usually designed by classical frequency response techniques based on the small signal model of converters. To harvest solar power, rechargeable batteries are used to store energy. Because output voltage of a solar panel varies constantly, a dc-dc converter is needed to regulate the charging and discharging of the batteries. This chapter will introduce several types of dc-dc converters.

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Small signal model of the converters will be first obtained. PID controllers will then be designed and implemented. A solar battery charger will be designed and implemented. Experimental results will be presented and examined.

BACKGROUND

Solar energy conversion is one of the most addressed topics in the field of renewable energy. Solar radiation is usually converted into two forms of energy: thermal and electrical energy. Solar electricity has applications in many systems such as rural electricity, water pumping and satellite communications.

In the past, solar power was usually used for large-scale grid connected system and small remote photovoltaic plants or stand-alone systems (Bica, 2008). Recent technological development in thin-film photovoltaics (PV) is leading to new generations of consumer portable solar panels. These new solar panels are light weight, durable, flexible, and have been reported to achieve power efficiencies of up to 10%. The portable solar panels make solar power readily available for mobile power needs such as outdoor enthusiast, expeditions and campers. It also provides portable solar power for the military to extend the run time of military devices including satellite communications, two-way radios, laptop computers, thermal imaging cameras, GPS, and etc. Therefore, solar power is expanding beyond its traditional applications.

Solar power is harvested and stored by charging rechargeable batteries. Older solar battery chargers were mainly developed for stationary situations such as solar house and RVs. Lead acid batteries are usually used because light weight is not a major factor to consider. However, since the appearance of the foldable and light weight solar panels, the need to develop solar battery chargers for more portable batteries such as Nickel metal

hydrid (NiMH) and Lithium-ion (Li-ion) batteries becomes essential.

Previous work has been done to compare battery charging algorithms for stand alone photovoltaic systems (Armstrong, 2008). Peak power from the solar panels was tracked for photovoltaic systems using various methods (Hua, 1998). To increase conversion efficiency, maximum power point tracking techniques as well as optimal control were studied and implemented (Boico, 2007; Masoum 2004).

Charging a battery requires a regulated dc voltage. However, the voltage supplied by a solar panel can vary significantly depending upon the day, time, weather condition and irradiation from the sun. In order to charge the battery with a regulated voltage, a dc-dc converter is connected between the solar panel and the battery. The output voltage, current and power can be regulated using feedback controllers (Mohan, 1995). In this chapter, the following dc-dc converters are discussed.

1. Buck converter (step-down)
2. Boost converter (step-up)
3. Buck-boost converter (step-down/step-up)
4. Cuk converter (step-down/step-up)
5. Sepic converter (step-down/step-up)

Of these five converters, buck converter and boost converter are the basic converter topologies. Buck-boost, Cuk and Sepic converters are derived based on the two basic topologies. In a dc-dc converter, the switching device such as transistor or MOSFET is switched on or off completely, therefore efficiency of dc-dc converters is generally higher than linear regulators.

A buck converter produces a lower output voltage than the input voltage. A boost converter produces a higher output voltage than the input voltage. Buck-boost, Cuk and Sepic converters are buck-boost type converters that produce an output voltage that is either higher or lower than the input voltage. A pulse-width-modulated

(PWM) signal is sent to the switching device to regulate the output voltage. By varying the duty ratio t_{on}/T_s of the switch, the output voltage can be controlled.

SWITCH-MODE POWER SUPPLIES

Switch mode dc-dc converters efficiently transform an unregulated input dc voltage to a regulated output dc voltage under the control of the pulse-width modulation (PWM) (Lee, 1993). Two basic topologies are the buck converter (step-down converter) and the boost converter (step-up converter). There are usually two modes of operation for the dc-dc converters: continuous mode and discontinuous mode. The inductor current never falls to zero in the continuous mode. In the discontinuous mode, the inductor current falls to zero during the time the switch is turned off. Only operation in the continuous mode is considered in this chapter.

BUCK CONVERTERS

The buck converter shown in Figure 1 converts the unregulated source voltage V_{in} into the lower output voltage V_{out} . The ratio of the ON time (t_{on}) when the switch is closed to the entire switching period (T) is defined as the duty cycle

$D = \frac{t_{on}}{T}$. The corresponding PWM signal is shown in Figure 2.

The equivalent circuit in Figure 3 is valid when the switch is on. The diode is reverse biased, and the input voltage supplies energy to the inductor, capacitor and the load. When the switch is open as shown in Figure 4, the diode conducts, the capacitor supplies energy to the load, and the inductor current flows through the capacitor and the diode (Ang, 1995). The output voltage is controlled by varying the duty cycle. During steady state, the ratio of output voltage over input voltage is D , which is given by (1).

$$\frac{V_{out}}{V_{in}} = D \quad (1)$$

BOOST CONVERTERS

A boost converter, shown in Figure 5, converts an unregulated source voltage V_{in} into a higher regulated load voltage V_{out} . When the switch is closed as shown in Figure 6, the diode is reverse biased, the input voltage supplies energy to the inductor, while the capacitor discharges into the load. When the switch is opened as shown in Figure 7, the diode conducts, both energy from the input voltage and stored in the inductor are supplied to the capacitor and the load, thus the

Figure 1. Buck converter

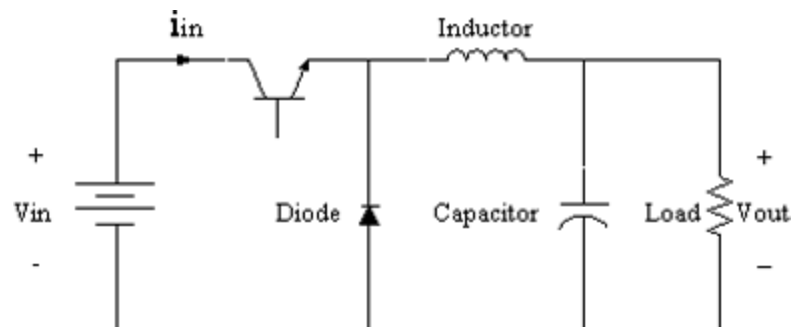
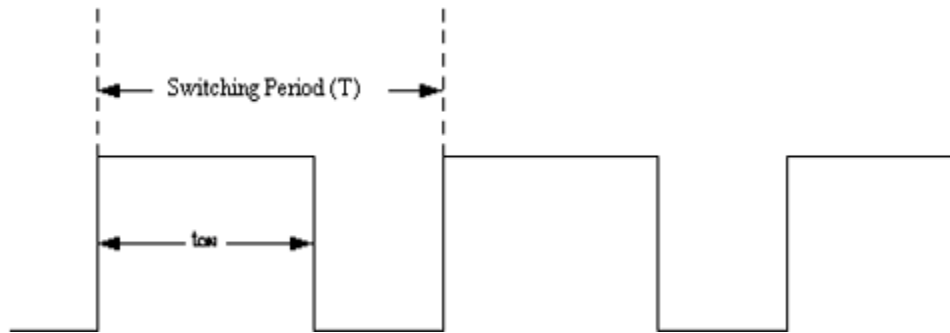


Figure 2. PWM signal to control the switches in the dc-dc converters



output voltage is higher than the input voltage. During steady state operation, the ratio between the output and input voltage is $\frac{1}{1-D}$, which is given in (2). The output voltage is controlled by varying the duty cycle.

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \quad (2)$$

STATE-SPACE AVERAGED MODEL FOR THE SWITCH MODE POWER SUPPLIES

The first step in the design of a controller is to obtain the mathematical model of the plant. Generally, it is one of the most time-consuming tasks in the design process. One of the most widely used models for dc-dc converters is based on state-space

averaging. This method combines the advantages of both state-space and averaging methods. It provides an accurate model at lower frequencies. It assumes that the output filter corner frequency is much lower than the switching frequency.

The procedure to obtain the state-space averaged model is now outlined (Severns, 1985). First, create the linear equivalent circuit for every state of the converter. The continuous mode has two states: switch closed and switch opened. Equivalent circuits for the buck converter appear in Figure 3 and Figure 4, and equivalent circuits for the boost converter are in Figure 6 and Figure 7. Second, write the state variable model for the linear equivalent circuit in each state. Inductor current (i_L) and capacitor voltage (v_C) are chosen as the state variables. V_{in} is the input voltage, V_o is the output voltage, D is the duty cycle, L is the filter inductance, C refers to the output filter capacitance, and R is the load

Figure 3. Equivalent circuit of the buck converter when the switch is closed

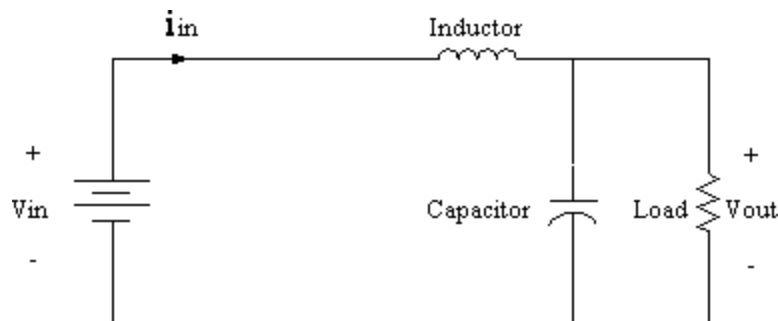
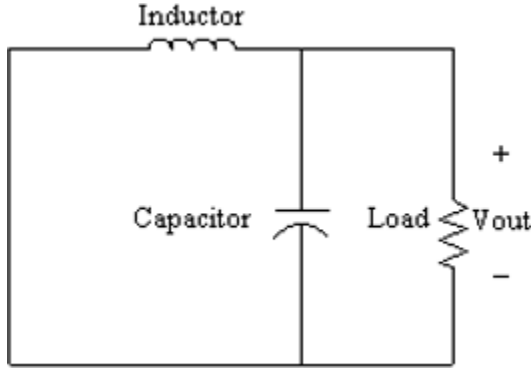


Figure 4. Equivalent circuit of the buck converter when the switch is open



resistance. The parasitic elements in the circuits are the equivalent series resistance (ESR) R_C of the output capacitance and the winding resistance R_L of the inductor. For the buck converter, the state variable equations for the circuit of Figure 3 are given in (3) and (4) (Sum, 1984).

$$\frac{di_L}{dt} = -\frac{1}{L} \left(\frac{RR_L + RR_C + R_C R_L}{R + R_C} \right) i_L - \frac{1}{L} \left(\frac{R}{R + R_C} \right) v_C + \frac{V_{in}}{L} \quad (3)$$

$$\frac{dv_C}{dt} = \frac{1}{C} \left(\frac{R}{R + R_C} \right) i_L - \frac{1}{C} \left(\frac{1}{R + R_C} \right) v_C \quad (4)$$

The state variable equations for the circuit of Figure 4 are given in (5) and (6).

$$\frac{di_L}{dt} = -\frac{1}{L} \left(\frac{RR_L + RR_C + R_C R_L}{R + R_C} \right) i_L - \frac{1}{L} \left(\frac{R}{R + R_C} \right) v_C \quad (5)$$

$$\frac{dv_C}{dt} = \frac{1}{C} \left(\frac{R}{R + R_C} \right) i_L - \frac{1}{C} \left(\frac{1}{R + R_C} \right) v_C \quad (6)$$

For the boost converter, the state variable equations for the circuit of Figure 6 are given in (7) and (8).

$$\frac{di_L}{dt} = -\left(\frac{R_L}{L} \right) i_L + \frac{V_{in}}{L} \quad (7)$$

$$\frac{dv_C}{dt} = \frac{1}{C} \left(\frac{R}{R + R_C} \right) i_L - \frac{1}{C} \left(\frac{1}{R + R_C} \right) v_C \quad (8)$$

The state variable equations for the circuit of Figure 7 are given in (9) and (10).

$$\frac{di_L}{dt} = -\left(\frac{R_L + (R / R_C)}{L} \right) i_L - \frac{1}{L} \left(\frac{R}{R + R_C} \right) v_C + \frac{V_{in}}{L} \quad (9)$$

$$\frac{dv_C}{dt} = \frac{1}{C} \left(\frac{R}{R + R_C} \right) i_L - \frac{1}{C} \left(\frac{1}{R + R_C} \right) v_C \quad (10)$$

Figure 5. Boost converter

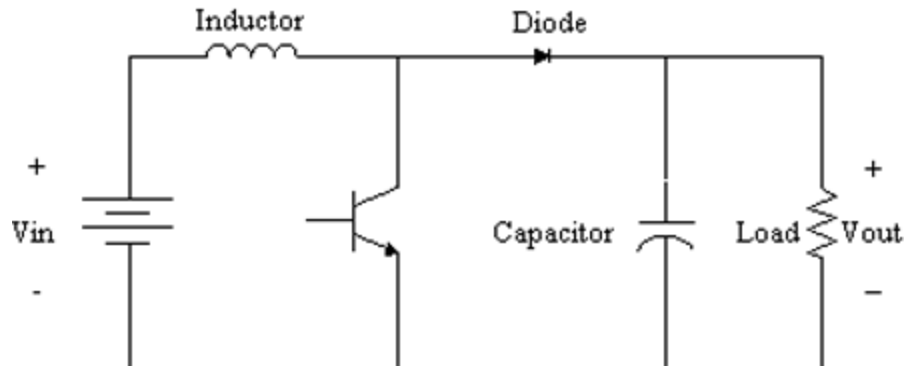
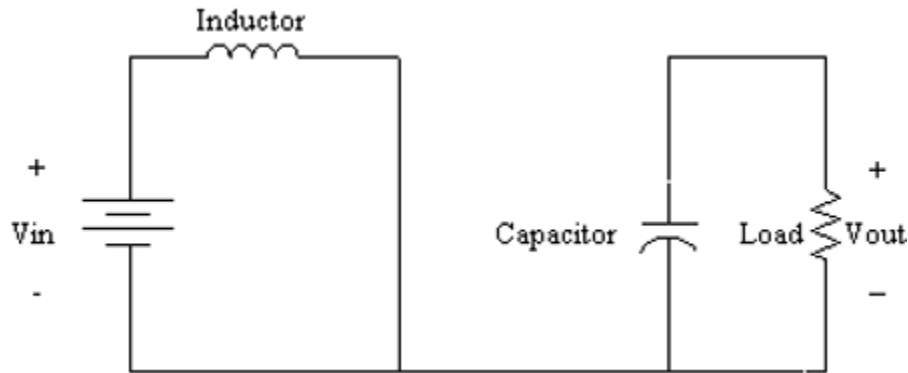


Figure 6. Equivalent circuit of the boost converter when the switch is closed



Third, use the value of the duty cycle as the weighting factor to combine the two equations into one. Fourth, generate the dc and small signal terms by perturbing the averaged equations, and remove the nonlinear cross products. Fifth, transform the small signal or AC terms into the s domain transfer function. After analysis, a small signal transfer function $\hat{v}_o(s) / \hat{d}(s)$ is obtained. $\hat{v}_o$ and $\hat{d}$ are the small-signal perturbations of the output voltage V_o and the duty cycle d near their steady state operating point V_o and D (Mohan, 1995).

STATE-SPACE AVERAGED MODEL FOR A BUCK CONVERTER

The buck converter's control-to-output transfer function derived by the standard state-space averaging technique is given by (11) (Severns, 1985).

$$\frac{\hat{v}_o(s)}{\hat{d}(s)} = \left(\frac{V_o}{D} \right) \left[\frac{1 + sRcC}{1 + s \left(RcC + [R / RL]C + \frac{L}{R + RL} \right) + s^2 LC \left(\frac{R + Rc}{R + RL} \right)} \right] \quad (11)$$

The input-to-output transfer function is given by (12):

$$\frac{\hat{v}_o(s)}{\hat{v}_s(s)} = \left[\frac{DR}{R + RL} \right] \left[\frac{1 + sRcC}{1 + s \left(RcC + [R / RL]C + \frac{L}{R + RL} \right) + s^2 LC \left(\frac{R + Rc}{R + RL} \right)} \right] \quad (12)$$

The control-to-output transfer function is utilized to design the controller. It is a common two-pole low pass filter, with a left half plane zero introduced by the ESR of filter capacitance. The cutoff frequency of the low pass filter is $\frac{1}{2\pi\sqrt{LC}}$. The magnitude falls with a slope of -40dB/decade at the cutoff frequency. The phase associated with it is a -180 degree phase delay.

The zero is at $-\frac{1}{RcC}$. There is a 20dB/decade magnitude rise at that frequency and the phase shift is 90 degrees. The magnitude of the transfer function depends on the duty cycle D . When D increases, the magnitude decreases; when D decreases, the magnitude increases. However, variations of D don't change the shape of the Bode plot of the transfer function. It only shifts the magnitude upward or downward.

MAIN FOCUS OF THE CHAPTER

Issues, Controversies, Problems

Digital signal processors (DSPs), microprocessors, and microcontrollers have been utilized in motor drives and uninterruptible power supplies for a number of years. Traditionally, regulation of the output voltage of dc-dc converters has been achieved through the use of analog control techniques. An analog control system operates in real

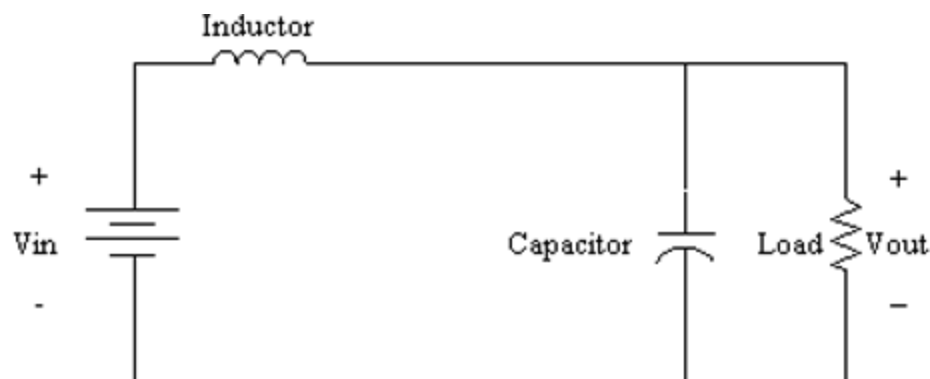
time and can have a high bandwidth. In addition, the voltage resolution for an analog system is theoretically infinite (Kuo, 1992). However, an analog system is usually composed of discrete hardware that must be modified to change controller gains or algorithms. In addition, the implementation of advanced control algorithms requires an excessive number of components. An examination of the literature indicates that interest is growing in the application of digital control techniques for regulating dc-dc converter output voltage (Vinsant, 1994; DiFiore, 1994; Vallittu, 1998; Boudreaux, 1996; Boudreaux, 1995; Kocybik, 1995; Bibian, 1999; Duan, 1999; Peng, 2001; Tso, 2001; Matsuo, 2000; Button, 2000; Tso, 2000; Forsyth, Forsyth; Matsuo, 1998; Gupta, 1997; So, 1995). The complexity of a digital control system is contained mostly in software. Once working properly, software is more consistent and reliable than a complex analog system. Digital processors also have the advantage of being less susceptible to aging and environmental or parameter variations. In addition, the processor can monitor the system, perform self-diagnostics and tests, and communicate status to a display or a host computer (Vinsant, 1994; DiFiore, 1994).

Technological advances have yielded micro-controllers and DSPs with the necessary on-board features to allow implementation of a digital controller for a dc-dc converter using a single chip. An

analog-to-digital converter (ADC) measures the output voltage and converts it to a corresponding binary number. A new duty cycle is calculated by the CPU using an algorithm stored in memory and passed to a PWM module, which controls the main switch or switches in the dc-dc converter.

Linear controllers for dc-dc converters are often designed based on mathematical models. To obtain a certain performance objective, an accurate model is essential. In a previous effort, linear proportional-integral-derivative (PID) controllers were designed for buck and boost converters (Guo, 2002; Guo 2003). The controllers were designed based on each converter's small signal model using frequency response and root locus design methods. The small signal model changes due to changes in operating point (Severns, 1985). Changes in the duty cycle only affect the magnitude of the buck converter's small signal model. But for the boost converter's small signal model, the poles and a right-half plane zero, as well as the magnitude of the frequency response, are all dependent on the duty cycle D . This makes the transfer function of the boost converter's small signal model a nonlinear function of the duty cycle. The right-half plane zero and the nonlinear nature of the boost converter's small signal model makes the control design for this converter more challenging from the point of view of stability and bandwidth.

Figure 7. Equivalent circuit of the boost converter when the switch is open



In order to achieve a stable and fast response, a feedback controller is designed for dc-dc converters. Output voltage from the solar panel varies significantly with the time of the day and season of the year. Load current of solar power systems also varies greatly. How to regulate the output voltage of dc-dc converters in the presence of input voltage and load disturbances in a solar power system remains an open research problem.

SOLUTIONS AND RECOMMENDATIONS

Boost Converter

The output-to-control small signal transfer function of a boost converter is shown in (13). It is obtained using standard state-space averaging techniques (Severns, 1985),

$$\frac{\hat{v}_o(s)}{\hat{d}(s)} = \frac{V_o}{D_o L_e C} \frac{(1 - \frac{sL_e}{R})(sR_e C + R_e / R + 1)}{s^2 + s \left[\frac{(R_e / D_o^2) + (R_e / D_o)}{L_e} + \frac{1}{CR} \right] + \frac{(R_e / D_o^2) + (R_e / D_o)}{L_e CR} + \frac{1}{L_e C}} \quad (13)$$

where D is nominal duty cycle, $L_e = L / (1 - D)^2$ and $D_o = 1 - D$. The transfer function is a second order, low-pass filter with two zeros. The low-pass filter's cut off frequency is at $\omega_c = \frac{1-D}{\sqrt{LC}}$. The zero in the left half plane is $\omega_{zl} = -\frac{1 + R_e / R}{R_e C}$, and the zero in the right half plane is $\omega_{zr} = \frac{(1 - D)^2 R}{L}$.

Variables ω_c and ω_{zr} are functions of nominal duty cycle D . In a closed-loop voltage-control system, the filter element will change as the duty cycle changes, which means the transfer function will change accordingly. This makes the transfer function of the boost converter a nonlinear function of the duty cycle. It makes the control design for

the boost converter more challenging from the point of view of stability and bandwidth.

For the experimental boost converter utilized in this chapter, the input voltage is 5 V, the output voltage V_o is 12 V, and the nominal duty cycle D is 58%. C is 1056 μ F, L is 250 μ H, and R is 25 Ω . The parasitic elements, R_e and R_{L_e} , are estimated from data sheets to be 30 m Ω and 10 m Ω , respectively. The frequency response of the boost converter when operating at steady state is also obtained using a Model 102B analog network analyzer by AP Instruments. There is a clear discrepancy between the theoretical model and the measured frequency response. Part of the discrepancy is because there is more damping in the actual plant than in the theoretical model. By fitting the experimental frequency response data using Matlab, a transfer function for the boost converter was constructed as shown in (14). The experimental frequency response and this transfer function are plotted in Figure 1. There is good agreement between the two curves. The transfer function in (2) has two zeros at -5.961×10^4 radians/s and 1.468×10^4 radians/s, and two conjugate complex poles at $(-4.126 \pm j6.1) \times 10^2$ radians/s.

$$\frac{\hat{v}_o(s)}{\hat{d}(s)} = \frac{-5.6956 \times 10^{-3} s^2 - 2.5589 \times 10^2 s + 4.9831 \times 10^6}{s^2 + 8.2525 \times 10^2 s + 5.4241 \times 10^5} \quad (14)$$

Boost Converter Controller Design

A PID and a PI controller are designed for the boost converter for operation during a start up transient and steady state, respectively. The derivative term in a PID controller is susceptible to noise and measurement error of the system, which could result in oscillation of the duty cycle during steady state. However, during transient, the derivative term is needed to reduce the settling time by predicting the changes in error. Therefore, PID and PI controllers are switched between transient and steady state to obtain fast and stable response. The

controllers were designed based on the measured small signal model of the boost converter in (14) using frequency response techniques.

One zero of the PID controller is placed at 260 radians/s, and the other zero is placed at 2600 radians/s. The transfer function of the PID controller is shown in (15). The Bode plot of the PID-compensated boost converter is shown in Figure 9. The bandwidth of the PID-compensated system is 1.83×10^3 radians/s, and the phase margin is 50 degrees.

$$G_c(s) = 0.567 + \frac{134.13}{s} + 0.000198s \quad (15)$$

A PI controller is designed for the steady state to reduce oscillations of the duty cycle. A pole is placed at the origin and a zero is placed at 600 radians/s. The transfer function of the PI controller is shown in (16). The Bode plot of the PI-controller-compensated system is shown in Figure 10. The bandwidth of the PI compensated system is 1010 radians/s, and the phase margin is 26.3 degrees.

$$G_c(s) = 0.1667 + \frac{100}{s} \quad (16)$$

Implementation of Linear PID and PI Controllers

The linear PID and PI controllers are implemented for the boost converter using an eZdsp F2812 from Texas Instruments. The eZdsp F2812 is a stand-alone evaluation module with a TMS320F2812 Digital Signal Processor (DSP). The TMS320F2812 is a 32-bit fixed point DSP controller with on-board flash memory. The CPU operates at 150 MHz. The TMS320F2812 supports peripherals used for embedded control applications, such as the event manager modules and a dual 12-bit, 16 channel ADC. The conversion period of the ADC is only 80 ns. The sampling and switching frequency of the linear PID and PI controllers is 150 kHz.

The continuous-time transfer function of the PID and PI controller in (15) and (16) are transformed into discrete-time domain using the backward integration method. The digital PID controller's transfer function is shown in (17).

Figure 8. Comparison of the frequency response obtained using the analog analyzer and from the generated transfer function

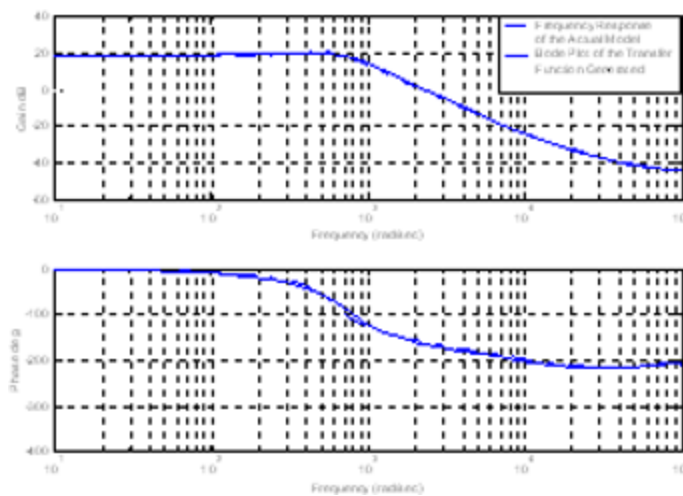
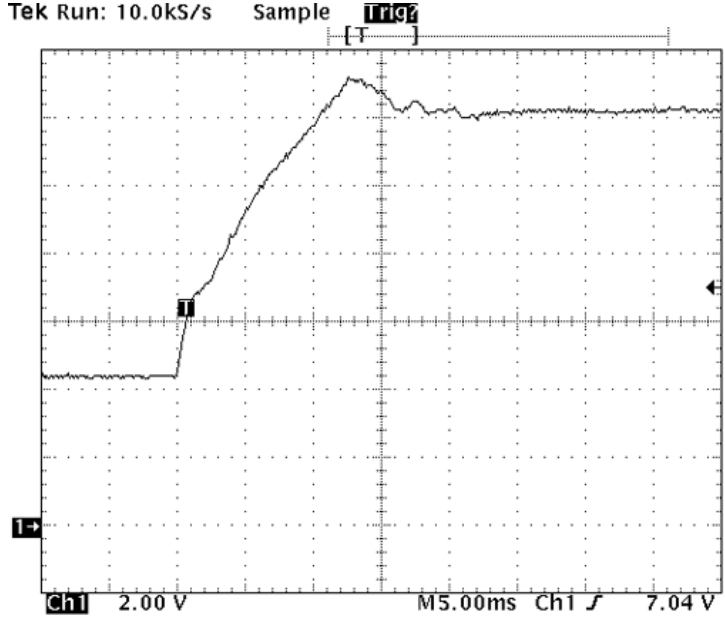


Figure 9. Start up transient response of the boost converter using the linear PID and PI control method (2V/div, 5ms/div)



$$G_C(z) = K_p + \frac{K_I T z}{z - 1} + \frac{K_D(z - 1)}{T z} \quad (17)$$

The difference equation to calculate a new duty cycle for the digital PID controller is written in (18).

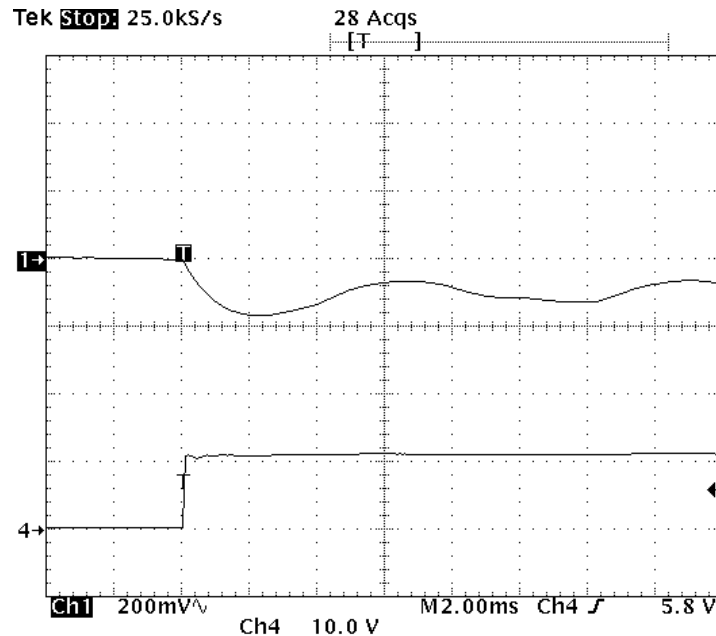
$$u[k] = K_p e[k] + K_I T \sum_{i=0}^k e[i] + \frac{K_D}{T} \{e[k] - e[k-1]\} \quad (18)$$

In the difference equation, $u[k]$ is the controller output for the k^{th} sample, and $e[k]$ is the error of the k^{th} sample. The error $e[k]$ is calculated as $e[k] = \text{Ref} - \text{ADC}[k]$, where $\text{ADC}[k]$ is the converted digital value of the k^{th} sample of the output voltage, and Ref is the digital value corresponding to the desired output voltage. $\sum_{i=0}^k e[i]$ is the sum of the errors and $\{e[k] - e[k-1]\}$ is the difference between the error of the k^{th} sample and the error of the $(k-1)^{\text{th}}$ sample. For the PI controller, the derivative gain K_D is zero.

The difference equation in (18) is a linear combination of feedback and control signals. A series of scalar multiplication and addition instructions can be used to implement the linear PID and PI controller. The TMS320F2812 DSP is optimized for implementation of digital filters. It has several instructions to multiply a number by a constant and add the previous product in a single instruction. Therefore, the implementation of the linear PID controller in real time is quite straightforward.

The PID controller is used during the start up transient to increase the speed of the transient response, while the PI controller is applied to obtain a more stable steady state response. The start up transient response is shown in Figure 9. The rise time is about 15ms, with about 10% overshoot. The transient response when the load changes from 0.24A to 0.48A using the linear PID and PI control method is shown in Figure 10, where the waveform on the top is the AC coupled voltage response, and waveform on the bottom is used to trigger at the instant of load transient. The settling

Figure 10. Transient response for the boost converter using the linear PID and PI control method when the load changes from 0.24A to 0.48A (200mV/div, 2ms/div)



time of the load transient response is about 10ms. There is a 100 mV steady state error.

DEVELOPMENT OF A SOLAR BATTERY CHARGER

Recent technological developments in thin-film photovoltaics (PVs), such as amorphous silicon and hybrid dye sensitized/PV cells, are leading to new generations of portable solar arrays. These new arrays are lightweight, durable, flexible, and have been reported to achieve power efficiencies of up to 10%. Since the emergence of these flexible and foldable solar arrays, there has become a need to develop solar battery chargers for more portable batteries, such as Nickel metal hydride (NiMH) and Lithium-ion (Li-ion) batteries for military and consumer applications.

Charging a battery requires a regulated dc voltage. However, the voltage supplied by a solar panel can vary significantly depending upon the day, time, weather condition and irradiation

from the sun. In order to charge the battery with a regulated voltage, a dc-dc converter is connected between the solar panel and the battery. The main components in the solar battery charger are standard Photovoltaic solar panels (PV), a deep cycle rechargeable battery, a Single-Ended Primary Inductance Converter (SEPIC) converter and a controller.

Different types of rechargeable battery were considered including lead acid, Nickel Cadmium (NiCd), Nickel metal hydride (NiMH) and Lithium ion (Li-ion) batteries. Among these batteries, Li-ion batteries have the highest energy density and relatively low self-discharge rates and no memory effect. A BB2588 Li-ion battery from Bren-Tronics, Inc is used for this project.

The SEPIC converter is a type of dc-dc converter that is able to convert unregulated input voltage into either a higher or lower output voltage. This allows the solar panel to charge the battery with a wider range of output voltage, thus flexibility is increased. Experimental results of the solar battery charger are evaluated.

SOLAR PANEL

Solar panels are made of many photovoltaic (PV) cells connected in series or parallel. The PV cell is a large area p-n diode with the junction positioned close to the top surface. When the cell is illuminated, electron-hole pairs are generated by the interaction of the incident photons with the atoms of the cell. The electric field created by the cell junction causes the photon-generated electron-hole pairs to separate. The electrons drift into the n-region of the cell and the holes drift into the p-region (Quintana, 1993).

The conversion efficiency of PV cells is defined as the ratio between the electrical power output and the solar power impinging the cell. The efficiency of the PV cells generally is less than 30%. This means that when a cell is illuminated, it will generally convert less than 30% of the irradiance into electricity. The continuing effort to produce more efficient and low cost PV cells results in different types of PV technologies. Major types of PV cells are single-crystalline silicon, polycrystalline, semicrystalline, thin films and amorphous silicon.

In this project, a PV-SC020J12 solar panel from Solar Cynergy is used. It has a nominal output voltage of 17 V and a nominal output current of 1.16 A, with maximum output voltage of 21.6 V and current of 1.31 A. The solar panel weighs only 2.27 Kg. Due to its small dimension and light weight, it can be moved very easily. Furthermore, it is waterproof and easy to install. The solar panel is tested by connecting an external resistor across the output. When the value of the load resistor changes, output voltage and output power of the solar panel changes. The test result is shown in Table 1. The output voltage of the solar panel can vary from 5.8 V to 19.6 V, and output power can vary from 3.92 W to 15.857 W.

RECHARGEABLE BATTERY

Older solar battery chargers were mainly developed to charge lead acid batteries. In order to reduce the weight of the solar power system for portable needs, there has become a need to develop more portable batteries including Li-ion and NiMH batteries.

Different types of rechargeable battery were considered including lead acid, Nickel Cadmium (NiCd), Nickel metal hydride (NiMH) and Lithium ion (Li-ion) batteries. Among these batteries, Li-ion batteries have the highest energy density and relatively low self-discharge rates and no memory effect. A BB2588 Li-ion battery from Bren-Tronics, Inc is used for this project. The dimension of the battery is 89.7 mm (length) $\times$ 30.9 mm (width) $\times$ 90.2 mm (height). The weight of the battery is 0.36 Kg. Nominal and maximum voltage is 14.4 V and 16.8 V respectively. Capacity of the battery is 2.2 Ah. Operating temperature range is -20°C to $+55^{\circ}\text{C}$.

The battery requires to charge at 16.5 V constant voltage, and 1 A maximum current. Charge is complete when current drops to 50 mA. To allow charging to proceed, 5 V dc needs to be applied through a 470 Ohm, 1/4 W resistor between the “charge enable” contact (+) and the negative contact of the main connector (-).

SEPIC CONVERTER

Dc-dc converters convert unregulated dc input voltage into regulated dc output voltage. In a dc-dc converter, a transistor or MOSFET operates as an electronic switch: either completely on or completely off. Power absorbed by an ideal switch should be zero. In practice, losses will occur in a real switch due to switching and conduction losses. Efficiency of a dc-dc converter is quite high compared to a linear regulator.

To charge the battery, a constant voltage of 16.5 V is required. However, the output voltage of

the solar panel will vary depending on the time of the day, weather condition and light illumination. Testing of the solar panel shows that the output voltage of the solar panel can vary from 5.8 V up to 19.6 V with different load current. To obtain a constant voltage of 16.5 V, a dc-dc converter is inserted between the solar panel and the battery to regulate the voltage. A single ended primary inductance converter (SEPIC) is chosen because it can convert the input voltage into either a higher or lower output voltage. The output voltage of SEPIC converter is non-inverted, while the output voltage of a buck-boost converter is inverted. Circuit schematics diagram of a SEPIC converter is shown in Figure 11. The Circuit parameters of the prototype SEPIC converter are listed in Table 2.

EXPERIMENTAL RESULTS

The solar battery charger is developed and tested in the laboratory. Experimental setup is shown in Figure 12. Efficiency of the SEPIC converter is tested with different input voltage from the solar panel. The efficiency η is determined by (19). Test result of the efficiency is shown in Table 3.

Table 1. Test of solar panel with changing load resistance

Load Resistance (Ω)	Output Voltage (V)	Current (A)	Power (W)
5	5.8	1.16	6.728
10	11.7	1.17	13.689
15	15.7	1.01	15.857
25	17.3	0.68	11.764
30	17.8	0.58	10.324
35	17.8	0.49	8.722
50	18.6	0.36	6.696
90	19.6	0.2	3.92

$$\eta = \frac{P_{out}}{P_{in}} \quad (19)$$

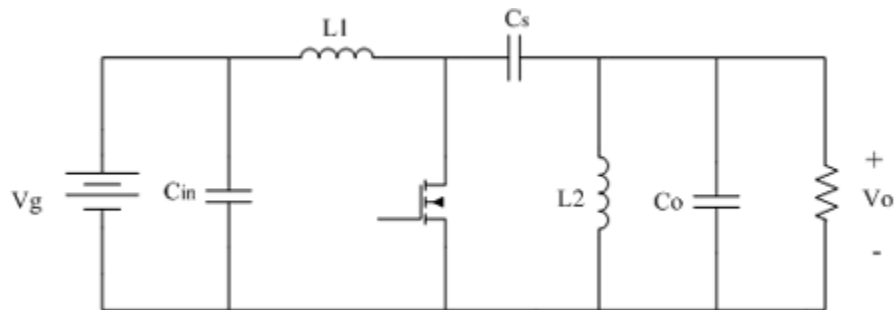
FUTURE RESEARCH DIRECTIONS

Portable solar battery chargers need to adapt to changing environmental conditions such as changing weather and changing current. New charge-control algorithms will continue to be developed to overcome this problem. Robust control algorithms will be able to adapt to variations in current and temperature. Different rechargeable batteries will need different charging and control algorithms. Advantages and disadvantages of various charging algorithms need to be compared and evaluated. Future research will be directed to develop a unified battery charger that is able to adapt to characteristics of different batteries. Optimum architecture for solar battery chargers will continue to be investigated. Maximum power point control can be applied to different architectures. How to improve efficiency of solar battery chargers remains as a research problem. To reduce the weight of solar battery charger, the power density of switch mode power supplies needs to be increased. In addition, it will be investigated how to reduce the cost of a solar battery charger.

Table 2. Circuit parameters of the prototype SEPIC converter

Parameter	Value	Units
Input capacitor, C_{in}	100	μF
Filter capacitor, C_s	200	μF
Output capacitor, C_o	200	μF
Filter inductance, L_1	2	mH
Filter inductance, L_1	2	mH
Load resistance, R	75	Ω

Figure 11. Schematics of a SEPIC converter



CONCLUSION

In this chapter, different architectures of dc-dc converters are discussed. For a buck converter, the output voltage is always lower than the input voltage. For a boost converter, the output voltage is always higher than the input voltage. For a buck-boost type converter, the output voltage can be either higher or lower than the input voltage. Small signal model and control of dc-dc converters

are discussed. Linear PID and PI controllers were designed and implemented for a boost converter. Linear PID and PI controller were designed based on the frequency response of the boost converter using frequency response techniques. The PID controller is used for start-up transient, while the PI controller is applied during steady state to achieve stable steady-state response. Design and implementation issues for the linear PID and PI

Figure 12. Experimental setup of the solar battery charger

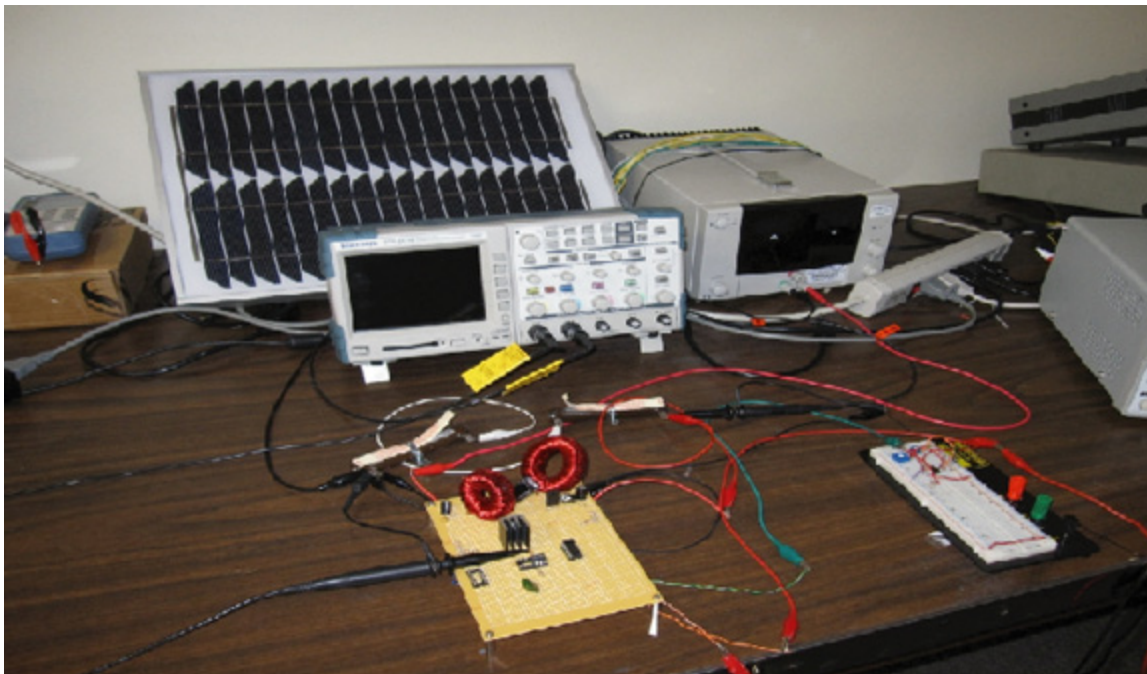


Table 3. Efficiency of the SEPIC converter with different input voltage

V_{in} (Volts)	Duty cycle D	I_{in} (Amps)	I_{out} (Amps)	P_{in} (Watts)	P_{out} (Watts)	efficiency
6	74.5%	0.72	0.2	4.32	3.28	75.93%
10	63.4%	0.43	0.2	4.3	3.28	76.28%
14	54.3%	0.34	0.2	4.76	3.28	68.91%
20	45.3%	0.25	0.2	5	3.28	65.60%

controller are discussed. Experimental results for a prototype boost converter are evaluated.

Design and implementation of a solar battery charger using a SEPIC converter is discussed in this chapter. The solar battery charger allows more portable usage for solar panels, such as outdoor enthusiast and soldiers on the move. The solar battery charger includes the following components: solar panel, Li-ion battery, SEPIC converter and controller. The SEPIC converter regulates the output voltage from the solar panels into a constant voltage, which is used to charge the battery. Efficiency of the SEPIC converter is tested and reported.

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KEY TERMS AND DEFINITIONS

Battery Charger: Power electronics equipment that regulate the charging and discharging of rechargeable batteries.

Boost Converter: A dc-dc converter that converts unregulated input voltage into higher regulated output voltage.

Buck Converter: A dc-dc converter that converts unregulated input voltage into lower regulated output voltage.

dc-dc Converter: Switch mode power supplies that converts unregulated dc input voltage into regulated DC output voltage.

Digital Control: Controller that uses microcontrollers or digital signal processors to implement control algorithms.

Efficiency: Ratio of output power over input power.

Proportional-Integral-Derivative (PID) Control: One of the most widely used compensator in feedback control systems. It uses proportional, integral and derivative terms to obtain both fast transient response and no steady state error.

Chapter 2

Solar Energy Storage: An Approach for Terrestrial and Space Applications

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ABSTRACT

With the urgent need to harvest and store solar energy, especially with the dramatic unexpected changes in oil prices, the design of new generation of solar energy storage systems has grown in importance. Besides diminishing the role of the oil, these systems provide green energy which would help reducing air pollution. Solar energy would be stored in different forms of energy; thermal, electric, hybrid thermal/electric, thermochemical, photochemical, and photocapacitors. The nature of solar energy, radiant thermal energy, magnifies the role and usage of thermal energy storage (TES) techniques. In this chapter, different techniques/technologies for solar thermal energy storage are introduced for both terrestrial and space applications. Enhancing the performance of these techniques using nanotechnology is introduced as well as using of advanced materials and structures. The chapter also introduces the main features of the other techniques for solar energy storage along with recent conducted research work. Economic and environment feasibility studies are also introduced.

INTRODUCTION

This book chapter is an effort to provide different techniques/technologies for solar energy storage and to analyze their economic and environment effects. The chapter involves also a pool for recent conducted research work in this vital field. The first section includes storing the solar energy in the form of thermal energy through phase change

materials, PCMs. In this context; the deployment of different types of PCMs in terrestrial applications is introduced as well as investigating and predicting their thermal characteristics numerically and experimentally. A negative aspect of PCMs is that most of these materials suffer from inherent low thermal conductivity. Hence, the second section introduces different techniques to enhance the thermal performance of PCMs. On

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the other hand, many studies have been conducted to investigate the enhancement of the thermal conductivity of PCMs using porous matrices. In general, this technique would present several advantages such as achieving high external heat transfer coefficient, very low bulk density, and good mechanical properties. Accordingly, the third section proposes utilizing of PCMs combined with solid porous matrices in thermal energy storage systems. In space applications, solar energy storage is a critical task and using PCMs in energy storage in space applications is very useful due to their higher energy to weight ratio. Consequently, the fourth section includes employment of PCMs in space applications. Nanotechnology and solar energy are being combined by many researchers to establish new generation of solar cells and to develop superior efficient solar energy storage systems based nanocomposites. Therefore, the fifth section introduces the role of nanotechnology in solar energy storage systems. The sixth section aims to present other techniques for solar energy storage. Hybrid Thermal Energy Storage Systems, (HTESS); is proposed to manage simultaneously the storage of heat from solar and electric energy. Another techniques are the Aquifer Thermal Energy Storage (ATES) and Underground Solar Thermal Storage systems. The general objective of these techniques is to provide heating and cooling by storing solar heat underground in summer and cold in winter. Photosensitizer in Photogalvanic cell for storage and conversion of solar energy and the photocapacitors are introduced in the sixth section as well. The seventh section includes economic and feasibility studies for solar energy storage systems. The eighth section incorporates solutions and recommendations for establishing new techniques and enhancing the performance of existing ones for solar energy storage. The ninth section includes, the future research directions and conclusions. The tenth section includes the references.

SOLAR THERMAL ENERGY STORAGE

In many parts of the world, direct solar radiation is considered to be one of the most potential source of energy. However, the large-scale utilization of this form of energy is possible only if the effective technology for its storage can be developed with acceptable capital and running costs (Kenisarin & Mahkamov, 2007). Thermal energy storage (TES), is of great importance in a wide variety of energy applications especially in solar energy storage applications. Thermal energy can be stored as a change in internal energy of a material as sensible heat, latent heat and thermo-chemical or combination of these techniques (Olofsson and Bengtsson, 2008). In his comprehensive study, Dincer (1999) introduced a discussion of the evaluation and the selection of sensible and latent heat storage technologies, systems and applications in the field of solar energy. Several issues relating to energy storage were examined from the current perspective. In addition, some criteria, techniques, recommendations, checklists on the selection, implementation and operation of energy storage systems were provided for the use of energy engineers, scientists and policy makers.

One of prospective techniques of storing solar energy in form of thermal energy is the application of phase change materials, PCMs. The phase change of PCMs falls into the category of moving boundary problems (Crank, 1987) and during their phase change process, both liquid and solid phases are presented and separated by a moving interface, mushy region (Mesalhy et al. 2005). PCMs store energy in both sensible and latent heat forms. Initially, these solid– liquid PCMs perform like conventional storage materials; their temperatures rise as they absorb heat. Unlike conventional (sensible) storage materials, when the PCM reaches the temperature at which they change phase (their melting point) they absorb

large amounts of heat without getting hotter. In the contrary, when the ambient temperature around the PCM drops, the PCM solidifies, releasing its stored latent heat (Elgafy & Lafdi 2010). PCMs can be used in both; terrestrial and space applications. Essentially, PCMs are used in solar domestic hot water heating. Additionally, using PCMs in solar energy storage in space applications is very useful due to their higher energy to weight ratio (Lafdi et al. 2008). Different types of PCMs and their properties are presented by Kenisari & Mahkamov (2007). In the following sections; the potential of using PCMs in terrestrial and space application will be discussed.

Solar Energy Storage in PCMs for Terrestrial Applications

Conventional types of PCMs are paraffin waxes, mineral salts, metal alloys, and some types of polymers. Studying of the potential of using a particular PCM as energy storage mediums, in general, would be achieved analytically, experimentally, numerically, or by using a combination between these three approaches (Mesalhy, 2005).

The analytical solutions of phase change are mainly based on solving the Stefan moving boundary problems (Elgafy et al., 2004). An extensive review for the analytical techniques for solving such moving boundary problems is presented by Crank (1987) and Zerroukat & Chatwin (1994). Bareiss & Beer (1984) studied analytically the temporal geometric shape, melting rates, and heat flux for melting of PCM inside a metallic isothermally heated copper tube. For contact melting, Moallemi & Viskanta (1984) developed a mathematical model for melting of a solid, which was continuously in close contact with a heat source. They assumed that the heat source and the solid phase are continuously separated by a very thin film in which the flow is predominantly in one direction. Following the same process Lacroix (2001) set a mathematical model for contact melting of a subcooled PCM inside a heated parallelepipedic

capsule. He simplified the momentum equation and solved it explicitly from the energy equation. His results indicated that the melted fraction from close contact melting at the bottom of the capsule was larger, by an order of magnitude, than that from the conduction dominated melting from the top. The steady close-contact melting occurring between a PCM and an isothermally heated flat surface in relative motion was investigated analytically by Hoseon et al. (1998). While, Soma & Dutta (1993) conducted theoretical and experimental work to describe the melting characteristics of paraffin wax encapsulated between two concentric cylinders. It was found that the melting time depends on the rate of natural convection; the higher the rate of natural convection the smaller the melting time. On the other hand Aghbalou et al. (2006) studied the exergetic optimization of a solar thermal energy system. The system consisted of a solar collector and a rectangular water storage tank that contains a PCM distributed in an assembly of slabs. The study took into account both conduction and convection heat transfer mode for water in the solar collector, and also the phase change process for the PCM in the storage tank. An analytical solution for the melting process in the PCM was also presented. They concluded that the exergetic optimization study of the PCM-slabs-SEST gives optimal melting temperature. Results shows that T_m ranges between 327 K and 363 K. To the contrary, Xiao et al. (2009) introduced an analytical approach to optimize the phase change temperature and the total amount of interior latent heat capacity in a lightweight passive solar room. The optimization was applied to a typical passive solar room in Beijing with interior PCM panels as energy storage components. The analytical average indoor air temperature, optimal phase change temperature, and the amount of interior latent heat capacity agree well with the simulated results, and the modeling program was validated with experimental data.

Many experimental works have been carried out to study melting processes of PCMs, to investi-

gate the heat transfer regimes during phase change processes, and to study melting characteristics of some PCMs. Wang et al. (1999) investigated the melting process in the vicinity of a heated vertical wall. It was found that during the melting process, three different heat transfer regimes were identified; these are pure conduction mode, transition mode, and convection mode. The role of natural convection on the solid-liquid interface during melting and solidification of Lipowitz metal and pure Gallium in a rectangular cavity were studied by Gau & Viskanta (1984; 1986). The measurements of both temperature distributions and temperature fluctuations were used as a qualitative indication of the natural convection flow regimes and structures of melting during the phase transformation. For melting, the measured melt volume and heat transfer coefficients were correlated in terms of relevant dimensionless parameters. For solidification, the measured volume of metal solidified on the wall was compared with predictions based on a one-dimensional model. Alternatively, Ho & Viskanta (1984) used a shadowgraph technique to study the melting of *n*-octadecane from an isothermal vertical wall. The shadowgraph technique was used to measure the local heat transfer coefficients at the hot surface, and the solid-liquid interface motion during the phase change was recorded photographically. For melting from heat flux wall (Debabrata & Yogendra, 2001) studied the melting of organic PCM, *n*-triacontane, in a side heated tall enclosure of aspect ratio 10, by a uniform dissipating heat source. Experimental visualization of melt front locations was performed. Their results showed that natural convection plays a dominant role during initial stages of melting. On the other hand, Jianfeng et al. (2001) studied experimentally the melting of a mixture of PCMs to investigate the enhancement of heat absorption of energy storage by using multiple phase change materials. The results showed that using multiple PCMs enhances the charging rate of the PCM energy storage. Sari & Kaygusuz (2002) and Baran & Sari (2003)

investigated experimentally palmitic acid and an eutectic mixture of palmitic and stearic acids as a PCM in a simple tube-in-tube heat exchanger. It was observed that the convection heat transfer in the liquid phase plays an important role in the melting process and the melting and solidification times can be changed by placing the PCM storage in different positions. Experimental results also showed that the eutectic mixture had good phase change and heat transfer characteristics during the melting and solidification processes, and it is an attractive candidate as a potential PCM for heat storage in latent heat thermal energy storage systems.

Conversely, knowing of the thermal behavior of a PCM in devices under periodic heat loads is crucial. Casano & Piva (2002) studied numerically and experimentally the periodic heating of a plane slab of PCM from the top by applying a sinusoidal heat flow. They found that the system is able to act as a damper of entering energy oscillations and the heat flux emerging from the output surface was almost constant.

To the contrary, there are different approaches for solving problems of heat transfer and fluid flow during phase change processes. In the past, finite difference methods have been frequently used for problems of flow and heat transfer in regular geometries (Patankar, 1980; Tanahill et al., 1997). Mittal et al. (1999) developed a method for solving flow and heat transfer around immersed bodies using orthogonal grid, but this still needs a lot of programming effort. On the other hand, finite volume method is a very powerful tool for solving heat transfer and fluid flow equations. For curvilinear systems, finite volume technique has been found to be very efficient in conjunction with numerical grid generation (Pope, 1978; Rhie & Chow, 1983). Numerical grid generation has become an integral part of the curvilinear control volume technique. The literature on grid generation techniques is vast and growing rapidly. Extensive surveys have been presented by Warsi et al. (1985) and Eiseman (1987). Damir & Greta

(1996) presented a new front tracking method to simulate time dependent two-dimensional dendritic solidification of pure substances. A numerical study of natural convection melting within an isothermal vertical cylinder was conducted by Yong & Lacroix (1995).

Conversely, Lagrangian methods can be used successfully in some of the phase-change problems in which the PCM is subjected to severe volume changes (Attinger & Poulidakos, 2003). In the same way Sripada et al. (2003) studied melting and rolling up due to surface tension of a metallic wire electrode heated from below. This problem was a three-phase problem (solid, liquid, and the ambient medium) with two simultaneous interfaces. The outer interface was tracked by orthogonal grid generation conforming with the evolving boundary surface at each time interval.

On the other hand, numerical grid generation with front fixing techniques has been used to solve phase change problems in a Lagrangian way. Dursunkaya & Odabasi (2003) used this technique to study the solidification of an infinitely long square prism. It was assumed that the liquid phase is at the melting temperature throughout the computation, so the convection motion effects were neglected. In the same way, Kamal & Maria (2003) performed a numerical study for the melting of PCM around a horizontal circular cylinder of constant wall temperature in the presence of the natural convection in the melt region. The phase change front was immobilized by using coordinate transformation and the method of control volume used to discretize the governing equations.

On the contrary, the Eulerian approach uses a fixed computational grid (Voller & Awaminathan, 1990). Fixed grid or Eulerian techniques have been used successfully by many authors to model phase-change problems (Brent et al., 1988; Asako et al. 1994; Asako & Faghri, 1999). Using of an enthalpy-porosity method Rady & Mohanty (1996) studied numerically the melting and solidification of a pure metal in a rectangular cavity. They showed that the results from the enthalpy-

porosity method agreed with the experimental data. Ghasemi & Molki used fixed grid enthalpy method to study the melting of an unfixed solid in a square cavity. The cavity was initially filled with the solid material and all four walls were heated to a temperature above the melting. This made the solid release as a result of melting near the walls. Falling of the solid in the melt and the buoyancy were the main factors affecting the liquid motion and the melting process. Following the enthalpy-porosity method (Sasaguchi et al., 1997) developed a numerical model to study solid-liquid phase change in a complicated geometry using a general coordinate system. Solidification calculations of pure water around a single cylinder or two cylinders were performed to check the validity of their model. Different configurations have been studied by Khillarkar & Mujumdar (2000). They considered melting of an organic PCM occupied between a square external channel and a circular inner tube. They studied the effect of Rayleigh number as well as heating from inside, outside or both walls at a temperature above the melting point of the PCM on the melting process.

(Scanlon and Stickland, 2004) investigated buoyancy driven melting and freezing using the commercial software FLUENT. The model used in this software is based on the fixed-grid enthalpy-porosity method. In this study, different materials were considered such as Lauric acid and water. Ilegbusi & Mat (1998) developed a hybrid model for the mushy region as a non-Newtonian semi-solid medium below the coherency point and a porous medium thereafter. The validity of their model was tested on the solidification of a generic binary alloy in a two-dimensional rectangular cavity. The predictions included temporal evolution of the flow and thermal fields and spatial distribution of the viscosity, velocity components and temperature. Additionally, Ilegbusi & Mat (2002) studied the solidification of an aqueous ammonium chloride ($\text{NH}_4\text{Cl}-\text{H}_2\text{O}$) solution inside a two dimensional cavity using the same model. A critical solid fraction was chosen as that cor-

responding to the coherency point, where a solid skeleton begins to form. Their numerical results showed that the solidification of a hypereutectic ($\text{NH}_4\text{Cl}-\text{H}_2\text{O}$) solution was mainly characterized by the rejection of solute at the mushy region.

On the contrary, in the Eulerian-Lagrangian method a fixed grid is used, and the interface is explicitly tracked by means of marker particles (Shyy et al. 1996; Udaykumar et al. 1999). So, this method has the advantage of simplicity like the fixed grid method as well as the ability to easily incorporate the surface forces arising from the elasticity of the interface or the surface tension like the Lagrangian method. More details for these methods are presented by Mesalhy (2005).

Techniques to Enhance Thermal Performance of PCMs

However, it is very challenging to find an ideal PCM that satisfies all the desirable properties (Fukai et al., 2000). A negative aspect of PCMs, like paraffin waxes, is that most of these materials suffer from inherent low thermal conductivity. When these PCMs are used in energy storing systems, their low thermal conductivities reduce the heat exchange rate during melting and solidification cycles and therefore the overall power of the phase change regenerator decreases. In case of space based power systems, this represents a great issue because of a large amount of heat should be stored or dissipated in a short period of time (Fukai et al., 2000). As reported by Bugaje (1997), the phase change (melting or solidification) time is the most important design parameter in latent heat storage systems. The thermal conductivities of PCMs could be enhanced using metal fillers, additives and/or fins (Hasnain, 1998). In the case of aluminum additives Bugaje (1997) found that the phase change time reduced significantly in heating and cooling processes. However, the metal fillers add significant weight and cost to the storage systems. Erk & Dudukovic (1996) utilized low-density additives such as porous silica catalyst

while Chapotard & Tondeur (1983) used activated carbon. They showed how the mean pore size of the additives could be of critical importance on the system performance. If it is too small, the PCM molecular motion will be hindered, thereby it will be very difficult to impregnate the porous media with the PCM, which will affect adversely on the latent heat storage capacity. Conversely, if the pores are too large, there will not be sufficient capillary force to retain the liquid wax. For activated carbons, waxes are well retained in micro-pores but they lose their phase change properties. Siegel (1977) studied the improvement of the solidification rate in molten salt dispersed with high thermal conductivity particles. He concluded that even though there was an improvement in heat transfer rate, there was a compensating effect due to the reduction in volume fraction occupied by the phase change material. Velraj et al. (1999) performed a detailed investigation for different heat transfer enhancement methods for the latent heat thermal storage system, such as using fins. They concluded that applying these methods was highly suitable for solidification enhancement. Experiments were performed by Cabeza et al. (2002) in a small energy storage device to study heat transfer improvement in PCM with the addition of stainless steel pieces and copper pieces. The PCM used was water. They noticed that addition of steel pieces did not increase the heat flux significantly but adding copper had a significant effect on enhancing the heat transfer process. Uros (2004) presented an experimental work to investigate melting and solidification of paraffin and the time dependent storage of heat in the PCM with and without steel fins for heat transfer enhancement. Through this study, new correlations between Nusselt and Rayleigh numbers were made. On the other hand, carbon fibers have a strong resistance to corrosion and chemical attack, which make them compatible with most PCMs (Elgafy et al., 2004). The thermal conductivities of carbon fibers are considerably high and their densities are less than 2260 kg/m^3 ,

which is lower than those of metals that are usually used as additives. Fukai et al. (2000) investigated the effect of using carbon fibers as additives by using two sets of carbon fiber architectures. In the first set, carbon fibers were randomly distributed into paraffin wax, while in the second set, carbon fibers were oriented parallel to the heat flow. The transient temperature response and the effective thermal conductivity of the composites were measured. They concluded that in case of random carbon fiber distribution, the fiber length had little effect on the thermal performance and the effective thermal conductivity of the system enhanced significantly by using brush type carbon fibers. As another solution for overcoming the undesirable PCM's characteristics, a mixture of different PCMs had been used. Jianfeng et al. (2001) studied experimentally the charging process of a cylindrical heat storage capsule filled with stearic acid, sliced paraffin and lauric acid as phase change materials. The geometric structure of the capsule made up of three coaxial red copper tubes. The surface temperature of the outer surface of the outer tubes is kept at constant temperature by putting it in a constant temperature water bath. The results showed that the using of multiple PCMs enhances the charging rate of the PCM storage.

Solid Porous Matrices Infiltrated with PCMs

On the other hand, many studies have been conducted to investigate the enhancement of the thermal conductivity of PCMs using porous matrices. In general, this technique would present several advantages such as achieving high external heat transfer coefficient, very low bulk density, and good mechanical properties. On the other hand, graphite matrix is known to be superior to porous metallic foams made of aluminum, copper or nickel (Elagfy & Lafdi, 2005). Also, Mauran et al. (1993) used a solid matrix made of graphite as a support for low thermal conductivity reactive salts. The effective thermal conductive for

the system has been enhanced significantly. Pay et al. (2001) proposed a supported PCM made of paraffin impregnated by capillary forces in a compressed expand natural graphite matrix. They found that the thermal conductivity of the composite was equal to that of the sole porous graphite matrix. Moreover, the composite presented the same anisotropy with respect to the compression axis. They concluded that, the compressed expanded natural graphite matrix induced a decrease in the overall solidification time and achieved more stabilization of the thermal storage power. Hoogendoorn & Bart (1992) reported that the low thermal conductivity of the PCM can be greatly enhanced by embedding a metal matrix structure in them. Alternately, Beckermann & Viskanta (1988) combined numerical and experimental studies for solid/liquid phase change in porous media with natural convection in the molten region. Their model was based on volume averaged transport equations, while phase change was assumed to occur over a small temperature range. Experiments were performed in a vertical, square enclosure using gallium and glass beads as the PCM and the porous matrix respectively. They showed that natural convection as well as the conduction in the solid has a considerable influence on the interface shape during both melting and solidification processes. All these works considered local thermal equilibrium between the solid matrix and the PCM, and this was acceptable because at most of the cases they are dealing with low thermal conductivity porous media. Harris et al. (2001) introduced a linearized enthalpy model that maintains a temperature difference between the PCM and the walls of the pore while it accepts a standard analytical solution technique. Mesalhy et al. (2005) studied numerically the thermal performance of PCM infiltrated inside porous matrix to be used as thermal energy storage mediums. Energy transport in their system was studied using two-equation model to be able to consider local thermal non-equilibrium condition. Finite volume technique was used with non-staggered

curvilinear body fitted grid. The practical aim was to define how much this porous matrix will improve the response time of the PCM storage. As shown in Figure 1, the physical domain was selected to be a two concentric cylinders which the volume located between them is filled with high porosity high thermal conductivity matrix. This matrix was totally saturated with low thermal conductivity phase change material. The inner cylinder surface was assumed to be at constant temperature T_h higher than the melting point while the outer cylinder surface was kept adiabatic. Due to the symmetry, only the half of this domain was considered. The numerical model was resting on solving the volume averaged conservation equations for mass, momentum, and energy with phase change (melting) in porous medium. The convection motion of the liquid phase inside the porous matrix is solved considering Darcy, Brinkman, and Forchheimer effects. The used grid is shown in Figure 2.

While, Figure 3 displays the dimensionless temperature gradient corresponding to different Fourier number and a zoom for the temperature contours and streamlines at Fourier number, $FO = 0.01667$. The temperature gradient decreases smoothly from bottom to top of the inner cylinder

surface due to the motion of the hot liquid to the top as a result of buoyancy force. A sharp decrease and increase in the temperature gradient can be seen at lower Fourier number. This happens due to the separation of the liquid from the cylinder surface, the temperature gradient drops sharply at the separation point and increases also sharply at the middle of the vortex due the cold liquid which comes in contact with the hot surface from the melting zone.

Additionally, a parametric study has been carried out to investigate the effect of inserting matrix with different porosities and different thermal conductivities on temperature field and on the storage heat absorption. The effect of insertion of fiber matrix with different porosities on the temperature and velocity field is shown in Figure 4. The figure shows the temperature contours and streamlines at early stage of melting process, Fourier number equal, $FO = 0.01667$, for thermal conductivity ratio (k_s/k_p) equal to 200. By comparing the case of pure PCM and the case of using matrix with porosity 0.95 we can see the increase of the melting rate in Figure 4b. As the porosity decreases the melting rate increases and also the convection motion of the liquid phase damps due to the decrease in the matrix perme-

Figure 1. Physical domain, Mesalhy, 2005

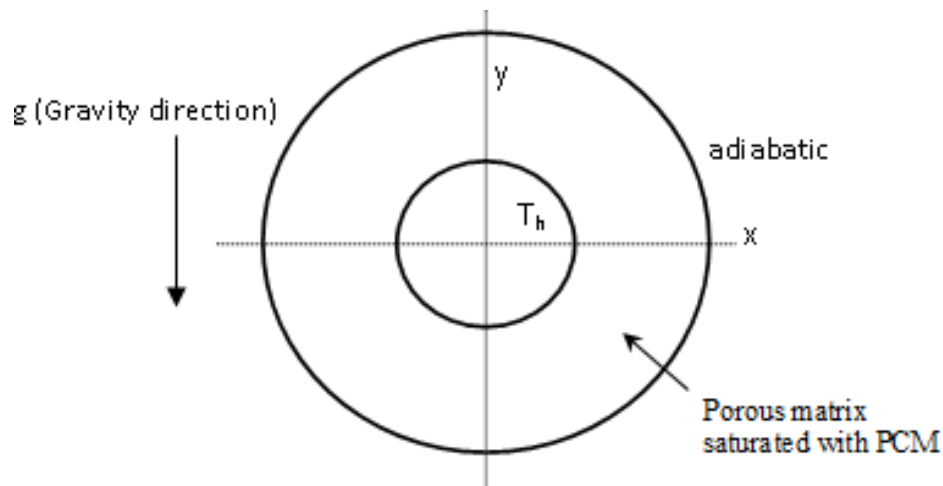
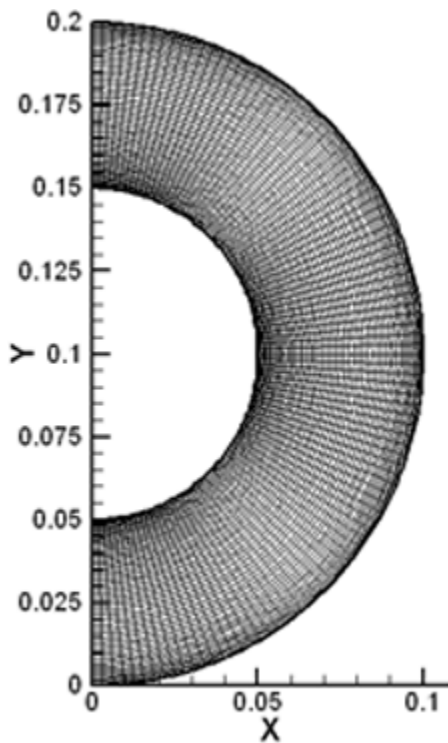


Figure 2. Grid proposed by Mesalhy, 2005



ability. The heat transfer regime tends to look like pure conduction case as the porosity of the matrix goes down. Temperature gradient and its fluctuations due to separation near the inner cylinder surface decreased with decreasing porosity as

shown in Figure 5 due to the increase in effective thermal conductivity and the decrease in the permeability of the porous matrix. As a conclusion, decreasing porosity can play a good and bad role on enhancing the melting process. The good one is that with lower porosity of high thermal conductivity matrix we can attain higher effective thermal conductivity but on the same time this will damp the liquid phase motion which naturally enhance the melting process.

To investigate the effect of changing the porous matrix thermal conductivity, the thermal conductivity ratio between the PCM and the porous matrix has been changes from 50 up to 200 with keeping porosity constant equal to 0.9. They have concluded that; increasing porous matrix thermal conductivity increases the melting rate especially at the lower region of the PCM storage. Finally, they reported that; by comparing the thermal performance of the storage with and without porous matrix, it was found that the presence of matrix has a great effect on the heat transfer and melting rate of the PCM. Decreasing the porosity of the matrix increases the melting rate but it also damps the convection motion. It was also found that the best way to enhance the response of the PCM storage is to use solid matrix with high porosity and high thermal conductivity.

Figure 3. Mesalhy, 2005. (a) Heat flux at the inner cylinder surface at different Fourier numbers. (b) Zoom for temperature contours and streamlines at $FO = 0.01667$.

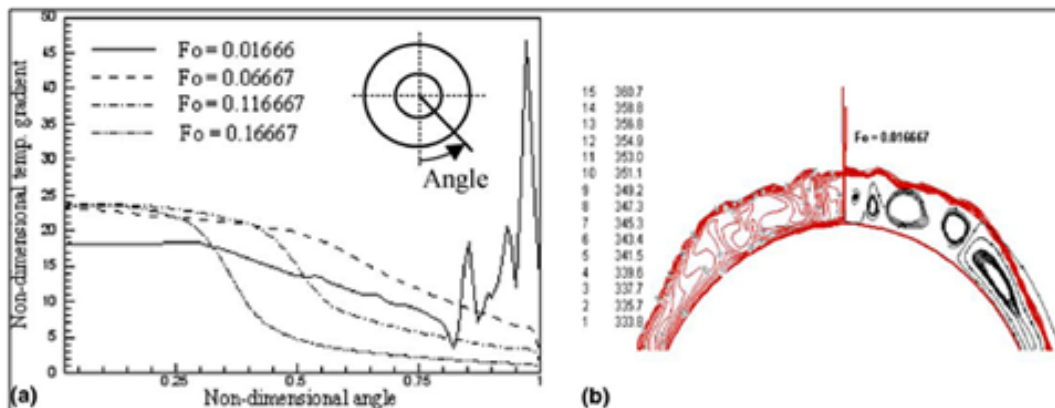
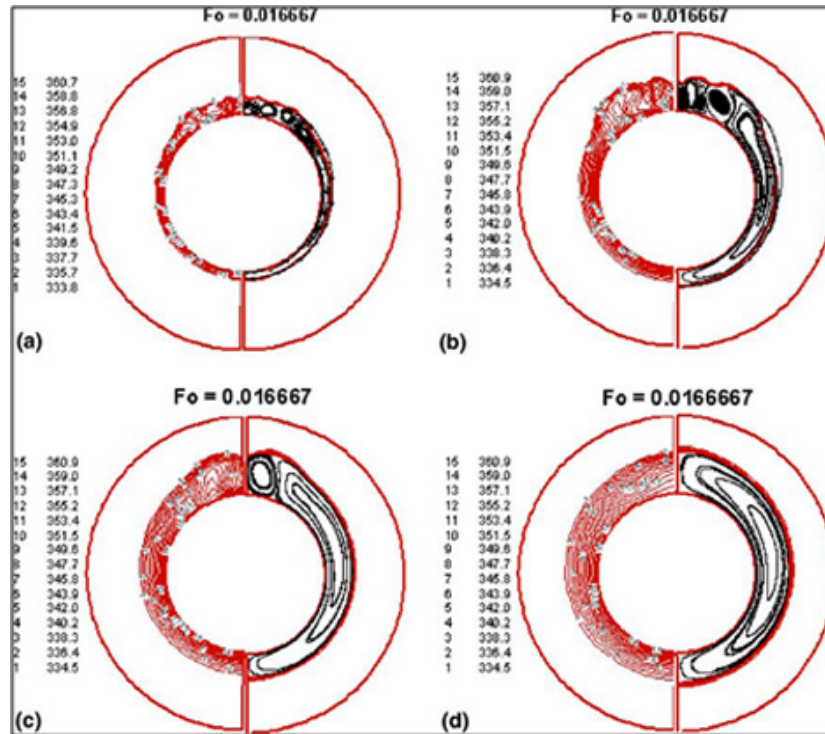


Figure 4. Temperature contours (left) and streamlines (right). (a) Pure PCM, (b) porosity 0.95, (c) porosity 0.90, (d) porosity 0.85, Mesalhy, 2005

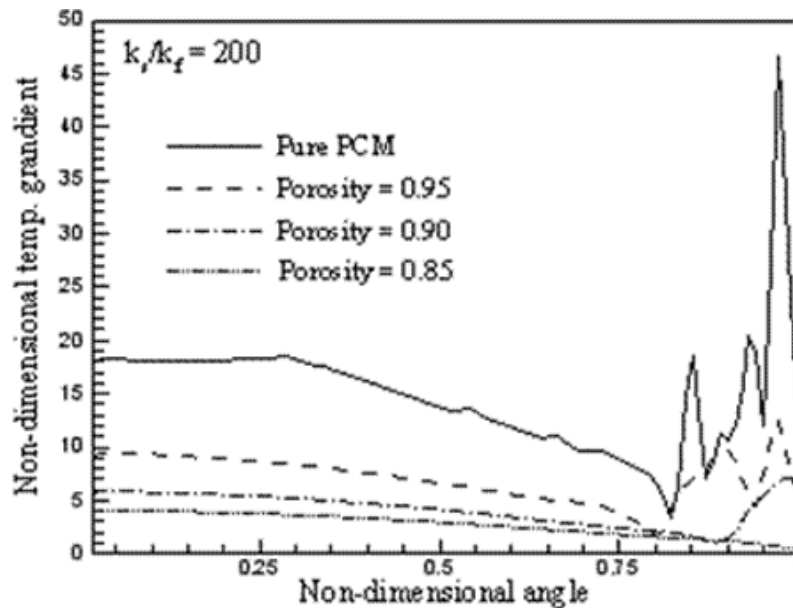


PCMs in Space Applications

In space applications, solar energy storage is a critical task and using PCMs in energy storage in space applications is very useful due to their higher energy to weight ratio. Yet, space applications require using high melting temperature PCMs. In space vehicles, the electrical power is generated by photovoltaic solar arrays. These solar arrays employ a concentrator to collect and focus the solar energy into PCM energy storage where it is converted to thermal energy. A fraction of this thermal energy is transferred to a circulating working fluid to run the heat engine and produce electrical power. The remaining thermal energy is used to melt the PCM contained in the energy storage. The PCM stores the excess energy by undergoing phase change at its transition temperature. This permits continuous operation of the heat engine during the substantial eclipse periods where there

is no solar energy available (Lafdi et al., 2008). The response time or the time for charging and discharging is a key factor in designing any energy storage system, especially applications that are restricted to a limited time for energy absorption. The charging or discharging time of the energy storage depends mainly on the thermal properties of the energy storage material. The higher the thermal conductivity the better response this energy storage can achieve. For Energy storage systems for spacecraft applications. Chow et al. (1996) concluded that the effective thermal conductivity of the PCM could be significantly increased by using smaller encapsulated PCMs enclosed in a container filled with a liquid metal. Hamada et al. (2000) also studied experimentally and numerically using carbon fiber chips and carbon brushes as additives to enhance the performance of PCM energy storage. They considered the effect of these additives on the thermal resistance beside

Figure 5. Non-dimensional PCM phase temperature gradient at $Fo=0.01667$ and $k_s/k_f=200$, Mesalhy, 2005



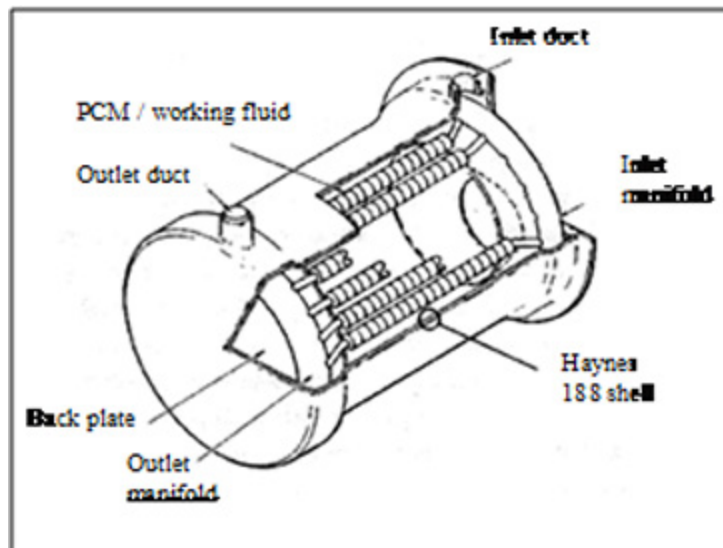
the heat transfer walls. They mentioned that the carbon fiber chips were effective for improving the heat transfer rate but they found that the thermal resistance near the heat transfer surface was higher than that for carbon brushes. As a result, the overall heat transfer rate for fiber chips was lower than that for carbon brushes even though the effective thermal conductivity of the bulk of the former was higher.

One of the most interesting designs is a solar receiver with a cylindrical cavity, the walls of which are lined with a series of hermetically sealed Haynes 188 containment canisters (Yu et al., 2004). The canisters are filled with a high melting temperature PCM and stacked to the working fluid tube, as shown in Figure 6. Using individual canisters in this design makes the design very reliable such that failure of a canister will affect only that individual canister itself. The most important factor in the design of such a solar heat receiver is the heat absorption rate or the storage response since the heat will be stored only during the specific time of sun exposure before eclipse.

Lafdi et al. (2008) studied the effect of using high thermal conductivity carbon foams to support the high melting temperature PCM on the solar receiver output power. The space between the outer and inner tubes of each canister has been filled with carbon foam saturated with LiF-CaF₂ as the PCM. The melting temperature of this PCM is about 767 °C. All the properties of this material are listed in "Table 1." The configuration and the dimensions of one canister are shown in Figure 7.

The heat delivered to the solar receiver was considered as a periodic radiation coming from the outer shell of the receiver. In the real case, this shell is subjected to a solar collector that provides the energy during the period of the sun exposure. The period of the sun exposure and eclipse was 40 minutes, 20 minutes exposure and 20 minutes eclipse. During the period of the sun exposure, the outer shell of the receiver is assumed to be at a constant temperature above the melting point of the PCM by 200 °C. During the eclipse time, the outer wall of the canister is assumed to

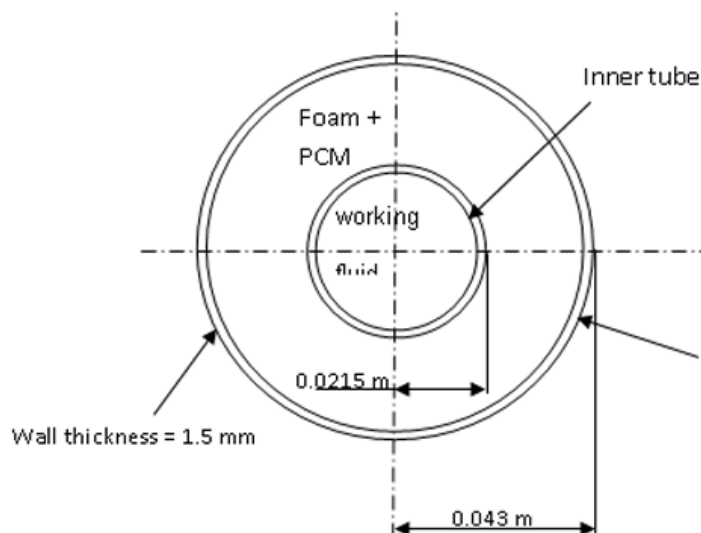
Figure 6. Solar receiver, Lafdi et al., 2008



be insulated. The output energy from the solar receiver is obtained continuously from the working fluid that is flowing inside the inner tubes. The simulation for this energy storage has been carried out for three consequent heating cycles. The change of the output power delivered to the working fluid from the solar receiver for pure PCM and for foam enhancer with different thermal

conductivity is shown in “Figure 8.” The average value of the output power increased with increasing the thermal conductivity of the enhancer foam, however, for pure PCM the output power was more stable and uniform. It was noticed that increasing the thermal conductivity of the foam over a certain limit did not bring any more improvement. For this particular case, it was above

Figure 7. Computational model for space application, Lafdi et al., 2008



15 W/mK, which means enhancing the PCM by more than 800%. This happened because after enhancing the PCM by this value for the assumed value of the outside shell temperature, the PCM is completely melted during the first cycle charging period as shown in “Figure 9.” Changing the pore size of the foam in this case did not bring any difference because of the absence of the liquid phase motion inside the porous media.

The same configuration for the solar receiver was used with another PCM, Ecosane, which has different properties, as shown in Table 2.

The same boundary conditions for the case of the solar collector have been considered except that the outer wall of the canister which has been subjected to a convection heat transfer from another hot fluid flowing around the outer tube during the charging period. At the discharging period, the outer tube wall also has been kept insulated. The working fluid inside the inner tube has been considered to be just below the PCM melting temperature. In this case, the motion of the molten phase of the PCM is considered and high porosity carbon foams are used to enhance the PCM thermal conductivity. The solid liquid interface is portrayed in “Figure 10” for the pure PCM between the two cylinders at different times during the three charging-discharging cycles. At the end of the charging period for the first cycle, 20 minutes, a considerable thickness of the PCM is melted. The melted region at the top and the

bottom of the tube became thicker because of the creation of Benard convection cells at the bottom and the motion of the hot liquid beside outer wall upward to the top region respectively. During the discharge time where there is no heat coming from the outer cylinder wall, the interface started to get thicker. This happened because of the heat diffusion inside the PCM and the solidification of some of the PCM during the discharging period. It is found that the PCM did not melt completely until the third charging cycle.

The output power is nearly zero for the pure PCM case during the first cycle because of its lower thermal conductivity as shown in Figure 11. The output power did not increase until the liquid solid interface nearly reached the inner cylinder wall. Adding carbon foam enhancer improved the energy absorption of the storage and increased the output power incredibly. The estimated value of the average output power using carbon foam of porosity 97% is about five times greater than that for using pure PCM. As shown in Figure 11, the enhancement of the output power decreased with reducing the foam porosity, it did not change significantly after reducing the foam porosity below 90%. As a result of considering the PCM liquid phase motion, changing the foam pore size affected the output power of the storage. Finally, they concluded that, for space applications, the average value of the output power of the new energy storage system (carbon

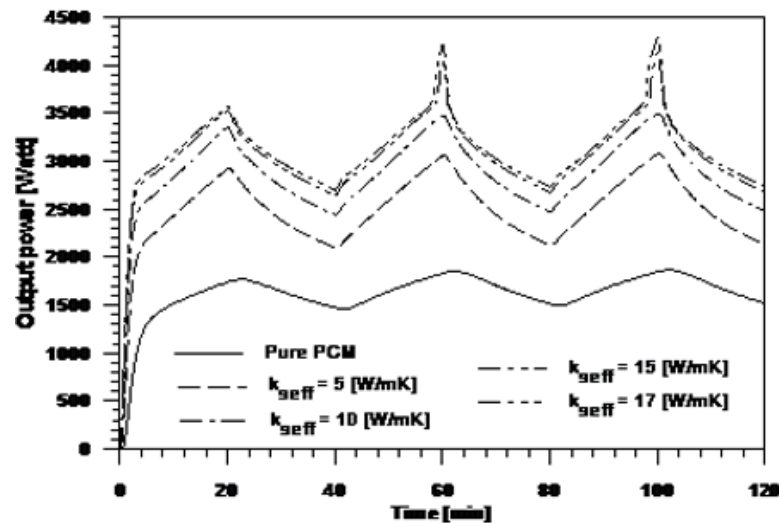
Table 1. High melting temperature PCM (LiF-CaF₂) properties, Lafdi et al., 2008

Property	Value	Unit
T _m	1040	K
k	3.8–1.7	W/mK
μ	0.0023	kg/m s
c _p	1770	J/kg K
ρ	2590	kg/m ³
L	816.0	kJ/kg
β	0.000287	1/K

Table 2. PCM, Ecosane properties, Lafdi et al., 2008

Property	Value	Unit
T _m	309	K
k	0.15–0.2	W/mK
μ	0.00415	kg/m s
c _p	2460	J/kg K
ρ	769	kg/m ³
L	247.3	kJ/kg
β	0.00085	1/K

Figure 8. Output power from the solar receiver for different foam thermal conductivity, Lafdi et al., 2008



foam infiltrated with PCM) has been increased significantly. For instance, the estimated value of the average output power using carbon foam of porosity 97% is about five times greater than that for using pure PCM.

Role of Nanotechnology in Solar Energy Storage Systems

Two of the hot-button fields of scientific study: nanotechnology and solar energy. They are being

combined by many researchers to establish new generation of solar cells and to develop superior efficient solar energy storage systems based nanocomposites. The nanocomposites have been significantly broadened to encompass a large variety of one, two, and three-dimensional systems made of distinctly dissimilar components mixed at the nanometer scale. Besides achieving composites that have desirable properties, there is also the possibility of gaining new properties, which are unknown in the parent constituent materials

Figure 9. Liquid fraction contours at the end of first cycle charging time, Time = 20 min, Lafdi et al., 2008

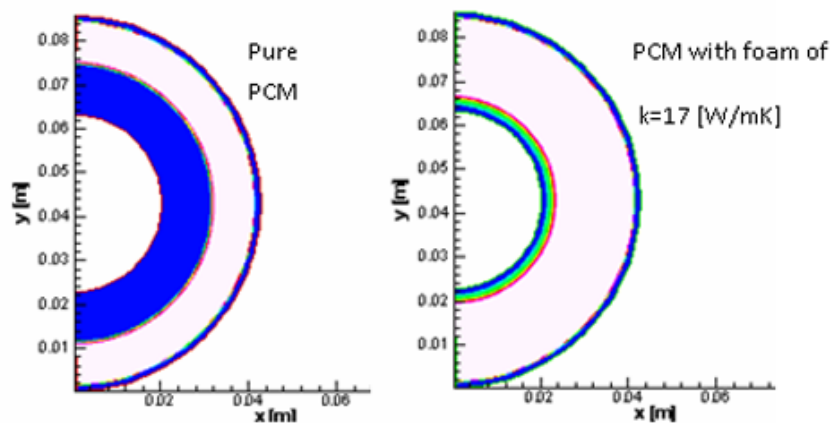
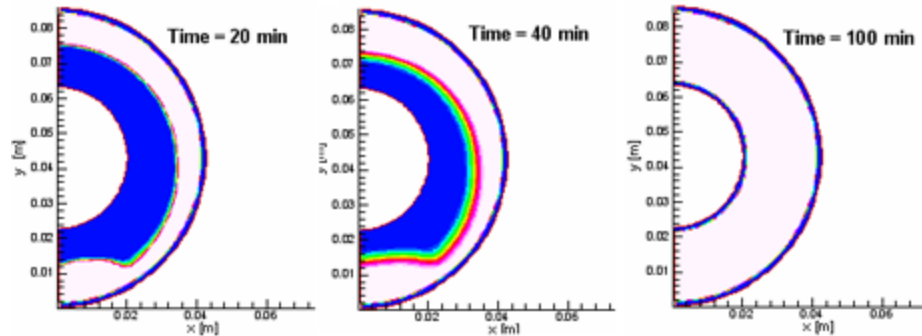


Figure 10. Liquid fraction contours for pure PCM at different times, Lafdi et al., 2008



(Elgafy & Lafdi, 2010; Elgafy & Lafdi, 2007). Elgafy and Lafdi (2005) designed and fabricated nanocomposites based carbon nanofibers filled polymer to be used as energy storage mediums. They used carbon nanofibers to enhance thermal performance of paraffin wax. Different mass ratios of carbon nanofibers were added into paraffin wax by shear mixing and melting processes. The thermal properties for the new nanocomposites (carbon nanofibers + paraffin wax) were measured experimentally and the transient temperature response for each one of them was recorded during the solidification process to predict the cooling rate and the storage energy. An analytical model was introduced to predict the effective thermal conductivity for the new nanocomposites. Also, a comparative study was performed to investigate the effect of carbon nanofibers surface characteristics on the enhancement of the phase change material thermal performance.

As shown in Figure 12, nanocomposite thermal conductivity increases significantly with increasing carbon nanofibers ratio into paraffin wax. This will enable the fabricated nanocomposite to store more efficiently the solar energy.

Figure 13a represents the solidification characteristic curve for pure paraffin wax sample, while Figure 13b represents the solidification characteristic curve for the nanocomposite sample of 1% CNFs content ratio. Figure 13a shows that the duration time elapsed during the latent heat

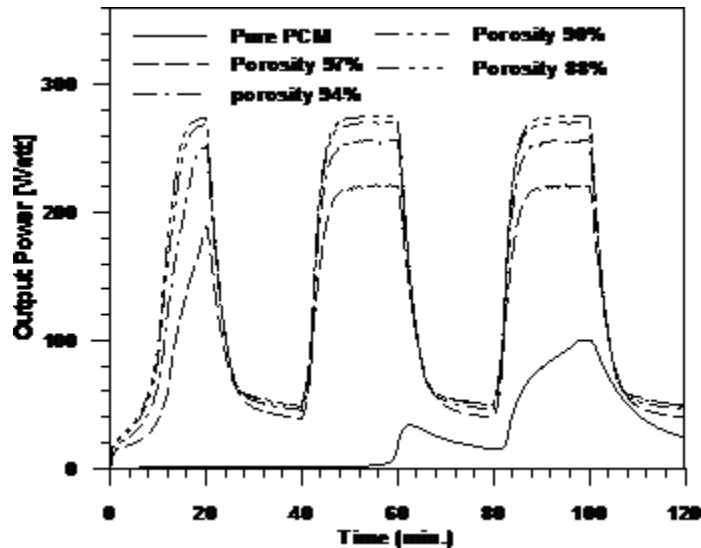
phase of pure paraffin wax, which is corresponding to 67 centigrade degrees, is about 450 sec, while it has a value of 350 sec for the nanocomposite sample of 1% CNFs content ratio. The decrease in the duration time indicates that the heat dissipation from the nanocomposite sample is higher than that of pure paraffin wax sample.

The output power from each sample during its solidification process was estimated by dividing the liberated energy from it over its solidification duration time. Figure 14 shows that the output power from the samples increases with the increase of the CNFs content ratio due to the enhancement of their thermal performance.

An analytical model was introduced to predict the effective thermal conductivity of CNFs based wax nanocomposites. The analytical solution was based on one-dimensional heat conduction approach for a composite cell of a low thermal conductivity PCM in which carbon nanofibers are dispersed. The effective thermal conductivity of the nanocomposites unit cell, K_e , is the resultant of the thermal conductivities of the three layers connected in series and it has the following predicted formula.

$$K_e = \frac{2(K_I \cdot K_{II} \cdot K_{III})}{2X \cdot (K_{II}) \cdot (K_{III}) + X \cdot (K_I) \cdot (K_{III}) + (2 - 3X) \cdot (K_I) \cdot (K_{II})} \quad (1)$$

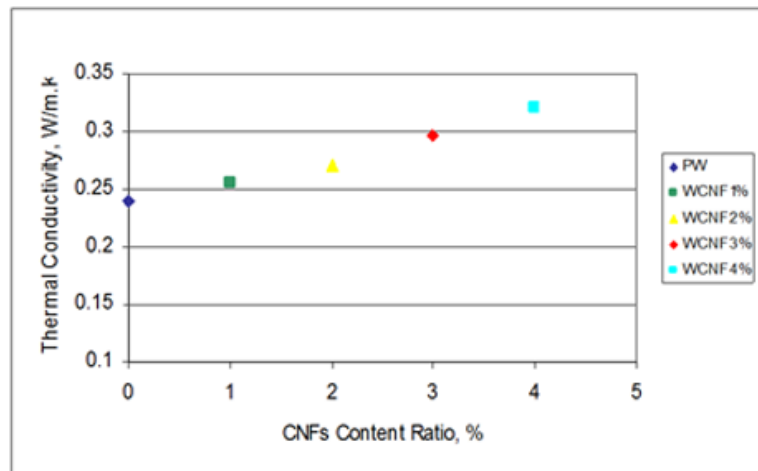
Figure 11. Changing of energy storage output power with time for using different porosity carbon foam, Lafdi et al., 2008



where K_I , K_{II} , and K_{III} are functions of the thermal conductivities of the used PCM, carbon nanofiber, and the geometrical distribution of the carbon nanofiber into the PCM. The coefficient “ X ” in equation (1) represents the effect of the content ratio of the carbon nanofiber, its aspect ratio, and its angle of inclination. Figure 15 shows a comparison between experimental findings obtained by

Lafdi & Matzek (2003) and the results of (Elgafy & Lafdi, 2005) for different angles of inclination. From the figure one can see that a good agreement between the analytical and experimental results is achieved at inclination angles between 25 and 45 degrees, which reflects the validity of the present analytical model within the experimental uncertainty.

Figure 12. Thermal conductivity for all samples, Elgafy & Lafdi, 2010



OTHER TECHNIQUES FOR SOLAR ENERGY STORAGE

Hybrid Thermal Energy Storage Systems

Hammou and Lacroix (2006) proposed a hybrid thermal energy storage system (HTESS) for managing simultaneously the storage of heat from solar and electric energy. In their model solar energy was stored during sunny days and released later during cloudy days or at night, and to smooth power demands, electric energy is stored during off peak periods and later used during peak periods. A heat transfer model of the HTESS was developed and validated with exact solutions and experimental data. Simulations were then performed to examine the effect of various storage materials and of the operating conditions on the thermal behavior of the HTESS. The results indicated that the consumption of electricity for space heating was minimized when the HTESS consists of a 0.15 m thick wall comprising spherical capsules 0.065 m in diameter filled with n-octadecane. With such a system, the electric energy consumption during the month of January may be reduced by as much as 30%. On the other hand, LeBreux et al. (2009) presented a controller for operating a hybrid thermal energy storage system (HTESS). The storage system accumulates solar energy during sunny days and releases it later at night or during cloudy days and, simultaneously, it stores electric energy during

off-peak periods and releases it later during on-peak periods. The control of the system rests on an anticipatory strategy and on a regulation strategy. The anticipatory strategy is based on a fuzzy logic and feed forward controller (FLFFC) that can handle simultaneously the storage and retrieval of both electricity and solar energy. It takes into account the weather forecasts for solar radiation and outside air temperature, and optimizes the off and the on-peak periods for electrical heating. The regulation strategy depends on a PID controller which regulates the air flow from an electric fan in order to maintain the room temperature at the set point. Numerical simulations were conducted over one to three-month winter periods to test the response of the controller. Results indicate that the proposed control system is far superior to traditional control systems. It remains robust and reliable even for cases in which the weather forecasts are of poor reliability and accuracy (5-day horizon weather forecasts with reliability of 50%, -10 K temperature accurate and -50% solar radiation accurate). The performance of the HTESS as well as the thermal comfort of the room is maintained in all situations and at all times. Moreover, the electricity consumption for space heating is minimized and 95% of this electricity is consumed during off-peak hours. Recently (Morrisson et al., 2008) proposed a study that aims to conceive, analyze and test systems of storage of thermal energy of the type PCM adapted to DSG (direct steam generation) technology for electricity

Figure 13. (a). Cooling of pure paraffin wax; (b). Cooling of nanocomposite with 1% CNF additives, Elgafy & Lafdi, 2010

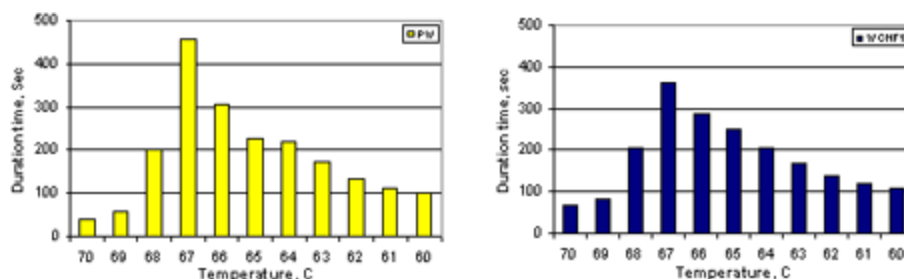
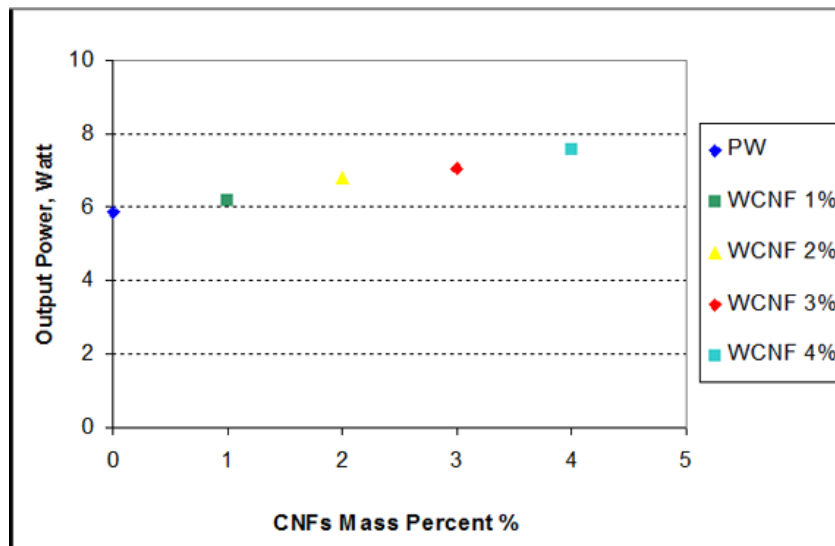


Figure 14. Output power during solidification process, Elgafy & Lafdi, 2010



production. A detailed model of heat transfer and fluid flow was proposed for numerical simulation of the storage system performance. Reasonable and justified assumptions and simplifications were introduced in order to define the most significant controlling parameters. Design and optimization procedure have been advised based on the present detailed and simplified models. At the level of the PCM, the advantages of the new high temperature graphite–salt composite proposed in the present study for application DSG storage systems have been demonstrated. Composites containing small percentage of graphite have been shown to significantly augment the thermal conductivity of PCM with relatively small decrease in the overall heat storage capacity. The increase of thermal conductivity implies an important increase of the charging and discharging rates of the unit, unit power as well as the production rates of water vapor. A major reduction in the total cost of the storage unit can be obtained by adopting these new composites. It is shown that, for the same system storage capacity and power the new graphite–salt composites make it possible to reduce significantly the overall length of necessary costly steel tubes.

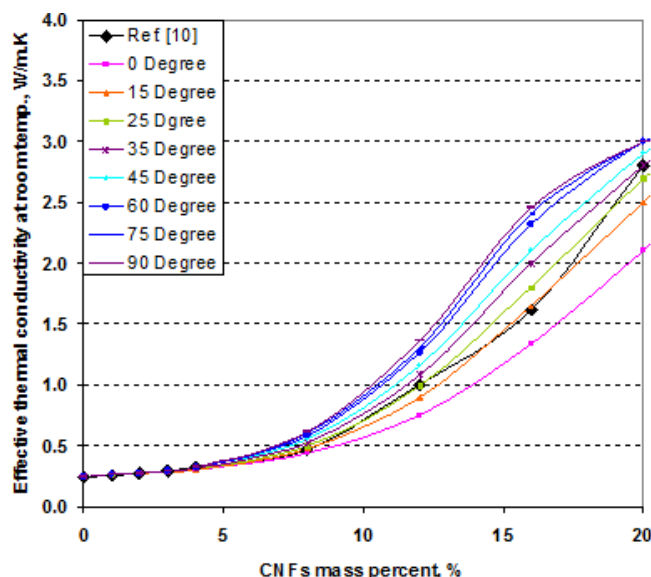
Aquifer Thermal Energy Storage (ATES)

Paksoy et al. (2000) proposed an Aquifer Thermal Energy Storage (ATES) system for heating and cooling of a hospital using solar energy coupled with seasonal thermal energy storage in an aquifer. The system was designed using solar energy in combination with Aquifer Thermal Energy Storage (ATES), that conserves a major part of the oil and electricity used for heating or cooling the Cukurova University, Balcali Hospital in Adana, Turkey. The general objective of the system was to provide heating and cooling to the hospital by storing solar heat underground in summer and cold in winter. As the main source of cold energy, ventilation air at the hospital and surface water from the nearby Seyhan Lake was used.

UNDERGROUND SOLAR THERMAL STORAGE SYSTEM

In the experimental study performed by Ozturk (2004), solar energy was stored daily using the vol-

Figure 15. Effective thermal conductivity versus percent of nanofibers with different angle of inclination, Elgafy & Lafdi, 2010



canic material with the sensible heat technique. The external heat collection unit consisted of 27m² of south-facing solar air collectors mounted at a 55.8 tilt angle. The dimensions of the packed-bed heat storage unit were 620.6m deep. The packedbed heat storage unit was built under the soil. The heat storage unit was filled with 6480 kg of volcanic material. Energy and exergy analyses were applied in order to evaluate the system efficiency. During the charging periods, the average daily rates of thermal energy and exergy stored in the heat storage unit were 1242 and 36.33 W, respectively. Since the rate of exergy depends on the temperature of the heat transfer fluid and surrounding, the rate of exergy increased as the difference between the inlet and outlet temperatures of the heat transfer fluid increased during the charging periods. It was found that the average daily net energy and exergy efficiencies in the charging periods were 39.7 and 2.03%, respectively. The average daily net energy efficiency of the heat storage system remained nearly constant during the charging periods. The maximum energy and exergy efficiencies of the heat storage system were 52.9 and 4.9%, respectively.

Photosensitizer in Photogalvanic Cell

A very little amount of solar energy (0.023%) has been utilizing by nature in the process of photosynthesis. A small fraction of this much solar input was utilized to fulfill the energy demands of whole world (Genwa & Chouhan, 2006). Photosynthesis is a natural photochemical reaction and a challenge to mimic such a reaction in laboratory till date. Genwa & Chouhan (2006) studied the role of heterocyclic dye (Azur A) as a photosensitizer in photogalvanic cell for solar energy conversion and storage; NaLS–ascorbic acid system. In their experiment; Sodium lauryl sulphate (LOBA), Azur A (LOBA), ascorbic acid (LOBA), sodium hydroxide (S.d. fine) were used. All the solutions were prepared in doubly distilled water and kept in dark-color containers to protect them from sunlight. A mixture of solutions of Azur A, sodium lauryl sulphate, ascorbic acid and sodium hydroxide was taken in a H-type glass tube. A platinum electrode (1.0 x 1.0 cm²) was immersed in one arm of H-tube and a saturated calomel electrode (SCE) was kept in other. The

arm containing platinum electrode was exposed to a 200 W tungsten lamp (Philips). A water filter was used to cut-off infrared radiations. A digital pH meter (Systronics 335) and a microammeter (INCO-65) were used to measure the potential and current generated by the system, respectively. The current–voltage characteristics were determined by applying extra load with the help of carbon pot (log 500 K) connected in the circuit. With this variable resistor (carbon pot) i – V curve was plotted. Light intensity was measured with the help of the solarimeter. The photopotential and photocurrent generated by this system were 770 mV and 160 μ A, respectively. The effect of different parameters like pH, diffusion length, electrode area, light intensity, temperature, etc. on the electrical output of the cell were observed, current–voltage characteristics of the cell have also been studied and mechanism has been proposed for the generation of photocurrent in photogalvanic cell. The performance of the photogalvanic cell was observed by applying an external load (necessary to have current at power point) after termination the illumination as soon as the potential reaches a constant value. The performance was determined in terms of $t_{1/2}$, the time required in fall of the output (power) to its half at power point in dark. It was observed that the cell could be used in dark for 110.0 min. The conversion efficiency of the system determined using the output at power point and the power of incident radiation. The system (at their optimum condition) was also exposed to sunlight. The converting efficiency calculated for this system as 0.5461%.

The Photocapacitor

Tsutomu & Murakami (2004) fabricated a light-driven self-charging capacitor as an efficient solar energy storage device. The device, which they named the photocapacitor, achieves in situ storage of visible light energy as an electrical power at high quantum conversion efficiency. The photocapacitor was constructed on a multilayered photoelectrode comprising dye-sensitized semi-

conductor nanoparticles/hole-trapping layer/activated carbon particles in contact with an organic electrolyte solution, in which photogenerated charges are stored at the electric double layer.

ECONOMIC AND ENVIRONMENT FEASIBILITY STUDIES

Paksoy et al. (2000) introduced economic and environment feasibility studies for their proposed system, Aquifer Thermal Energy Storage (ATES), to heat and cool a hospital. They reported that, in this ATES system, 7000 MW/year will be stored in the cold part of the aquifer at a mean temperature of +98°C. This storage is done in the winter during approximately 2000 hr. During storage approximately 500 MW will disappear as storage losses and as a result of this the temperature will rise about 18°C to +108°C. During summer, approximately 6500 MW will be used for cooling the hospital for roughly 3000 running hours (17 hr/day). This will replace a major part of the conventional cooling by chillers and save some 3000 MW of electricity. The ATES system will use approximately 250 MW electricity for the pumps in the

system. Its assumed that the average COP for conventional cooling is 2.0. For preheating of ventilation air by the ATES system 7000 MWh of energy is pumped from the warm part of the aquifer. To produce that heat, roughly 300 MW of electricity will be used to run the pumps involved. However, the preheating with the ATES system will save oil in the order of 1000 m³/year. The environmental benefits from this project will be reduction in energy consumption as electricity and fuel oil and replacement of chillers using ozone depleting Freon-12 gas. The savings in fuel oil (1000 m³/year) will approximately decrease the CO₂ emission by 2100 tons/year, SO_x by 7 tons/year, and NO_x by 8 tons/year. The replacement of 2 MW of current chillers using Freon-12 will result in a saving of approximately 0.7 tons/year of Freon-12.

SOLUTIONS AND RECOMMENDATIONS

As it is revealed from previous sections, establishing new techniques and enhancing the performance of existing ones for solar energy storage is vital for both terrestrial and space applications. Using of PCMs in solar energy storage systems seems to be the most effective/robust one due to the ability of PCMs to absorb/convey a large amount of energy during their phase change processes. However, it is very challenging to find an ideal PCM that satisfies all the desirable properties. A negative aspect of PCMs, is that most of these materials suffer from inherent low thermal conductivity. As a substantial technique; employing of high thermal conductivity solid porous matrices infiltrated with PCMs would enhance tremendously the performance of solar energy storage systems. By combining the two hot-button fields of scientific study, nanotechnology and solar energy, superior efficient solar energy storage systems based nanocomposites would be established. Other techniques for solar energy storage would be used; hybrid thermal energy storage systems, aquifer and underground thermal energy storage, and photocapacitors.

FUTURE RESEARCH DIRECTIONS

Solar energy storage has attracted many researchers to develop new efficient systems to harvest and store this green energy. One of the most important features for these systems is their ability to absorb and convey solar energy. Accordingly, the future research work would be focused on developing PCMs based nanocomposites with superior thermal characteristics. Also, the research area for establishing new energy storage systems that consist of solid porous matrices infiltrated with PCMs is a promising area since many variables should be considered; different PCMs, solid porous matrices with variable porosities and pore sizes,

and dissimilar thermal conductivities. Developing new hybrid systems is rich area for future work as well. Another future areas for research would be focused on manufacturing these new systems in an economical fashion to be available for different usages with suitable initial and running costs.

CONCLUSION

The design of new generation of solar energy storage systems has grown in importance due to the urgent need to harvest and store solar energy. Besides diminishing the role of the oil, these systems provide green energy which would help reducing air pollution. In this chapter, different systems for solar energy storage for terrestrial and space applications are introduced. These systems are based mainly on storing the solar energy in thermal energy forms. Such systems include the deployment of different types of PCMs in different solar energy storage applications. Unlike conventional (sensible) storage materials, when the PCM reaches the temperature at which they change phase (their melting point) they absorb large amounts of heat without getting hotter. In the contrary, when the ambient temperature around the PCM drops, the PCM solidifies, releasing its stored latent heat. Different techniques to enhance the thermal performance of PCMs have been introduced to magnify their capacities to store solar energy. One of the most effective techniques to achieve this goal is the infiltration of PCMs in conductive solid porous matrices. Parametric studies have been introduced to predict the key factors that manipulate the performance of the combination of the PCMs and porous matrices. On the contrary, nanotechnology is one of the hot-button fields of scientific study. Accordingly, the role of nanotechnology in solar energy storage systems has been introduced as well. Various types of nanocomposites with superior thermal characteristics have been proposed to be used as solar energy storage mediums. On

the other hand, Hybrid Thermal Energy Storage Systems, (HTESS) has been introduced to manage simultaneously the storage of heat from solar and electric energy. Additionally, the Aquifer Thermal Energy Storage (ATES) and Underground Solar Thermal Storage systems have been proposed to provide heating and cooling by storing solar heat underground in summer and cold in winter. The chapter introduces as well the Photosensitizer in Photogalvanic cell for storage and conversion of solar energy, and the photocapacitors. Economic and feasibility studies for solar energy storage systems have been presented. These studies show that using solar energy storage systems will replace a major part of the conventional heating and cooling systems. The environmental benefit from using these techniques will be the reduction in energy consumption from fuel oil, which will cause a decrease in the CO₂ emission. The solutions and recommendations for establishing new techniques and enhancing the performance of existing ones for solar energy storage systems are also incorporated in this chapter. A pool of essential, detailed and recent research work conducted in different areas for solar energy storage is provided in this chapter to be as a helpful reference for future research work in these areas.

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KEY TERMS AND DEFINITIONS

Graphite Foam: A macro-porous graphite with foam like structure.

Latent Heat: The quantity of heat absorbed or released by a substance undergoing phase change.

Nanocomposite: A multiphase material where one of the phases has one, two or three dimensions of less than 100 nanometers, (nm).

Nanotechnology: The science of manipulating atoms and molecules to fabricate materials, devices and systems.

Phase Change Materials: Materials that have the ability to store or conduct a large amount of heat during their phase change.

Solar: Radiant energy from the sun.

Thermal Conductivity: A measure of the ability of a material to conduct heat.

Thermal Energy Storage: Encompasses technologies that store thermal energy in energy storage reservoirs to be used afterward.

Chapter 3

Solar Photovoltaic Servo Tracking Controlled System

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ABSTRACT

Renewable energy has known a great interest during the last two decades. Solar energy is viewed as the cleanest renewable source of energy for the future since it is the least polluting and the most inexhaustible of all known energy sources. Subsequently, technologies that enable the use of solar energy focus on solar thermal collectors and on the photovoltaic effect of semiconductors to generate electricity directly from sunlight. In the case of solar energy, it is shown that optimal energy is obtained when the rays of the sun are incident normally on the collecting surface. Therefore, several techniques and experiments have been conducted recently to develop efficient solar tracking systems. Solar panel tracking systems optimize energy output of photovoltaic panels by positioning them to follow the sun's path throughout the day. The sun's position in the sky varies both with installation location, the seasons, and the time of day.

OBJECTIVES

Currently, most solar panels have fixed orientation to the sky and do not turn to follow the sun. To increase the unit area illumination of sunlight on solar panels, a solar tracking electricity generation system is designed. The design mechanism holds the solar panel and allows the panel to track the sun's movement during the day and improve the overall electricity generation. This system can achieve the maximum illumination and energy concentration and cut the cost of electricity by

requiring fewer solar panels, therefore, it has great significance for research and development. Moreover, Electro-optical control unit tracks the sun by a solar detecting device that is sensitive to solar radiance. Simple equipment such as phototransistors and DC motor are employed in the device of our working station. Furthermore, an analog operational-amplifier PD based controller is implemented to improve the time response of the tracking system. Finally, simulation and experimental results are demonstrated to verify the effectiveness of the light tracking servo system.

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The major objective is to design an electro-optical solar servo tracking system of photovoltaic panel in order to increase its overall efficiency using phototransistors, DC motor and PD controller such that

1. Derive the overall closed-loop controlled dynamical model.
2. Obtain all parameters related to electro-optical system.
3. Design a PD controller such that the settling time of the overall system does not exceed three seconds with a maximum overshoot of 50%.
4. Design a Lag Compensator.
5. Demonstrate the design using both simulation and experimental implementation.

INTRODUCTION

An optimal control on two axes and design for solar tracker which called altitude and azimuth is challenge. The phototransistor with the shade that blocks the screen was employed by Singthong as a detector of solar beam radiation (2010). The height of the screen determined the sensitivity operation or period of tracking in this solar tracker. The phototransistor is particularly designed to detect solar beam radiation thoroughly through the two axes with the operating time. The mechanism of this solar tracker is that it has a capacity of solar tracking in every 10 min, approximately, which respond in terms of time at about $37^\circ/\text{sec}$ with and operating point at 0.3 sec. The solar tracker obtained an average deviation at about $2.5^\circ/\text{hour}$. In weak sunlight however, the value varies and fluctuates rapidly depending on sky condition. There is only average of 2.5° error shown. The experiment also shows that the error rate diminishes as the solar radiance expand.

A low cost and an easy to implement solar tracker system is presented by Louchene, Benmakhlouf and Chaghi (2007). The design of the

system is based on the fuzzy reasoning applied to crisp sets. In this case, it can be easily implemented on general purpose microprocessor systems. Four light sensitive devices, such as LDR, photodiodes or phototransistors are mounted on the solar panel and placed in an enclosure. The four light detectors are screened from each other by opaque surfaces. Each pair of the light sensors is used to inform the controller on the orientation of the solar panel vertically and horizontally respectively.

A two-axes equator based tracking mechanism with computer control for solar photovoltaic modules has been designed, fabricated and tested by Patil, Nayak and Sundersingh (1997). The performance of the system is quite satisfactory; the tracking error is quite small. Tracking leads to an increase in the output of the PV modules typically by about 30%. The operation of the tracker is found to consume a very small fraction of the output power.

A solar tracking generating power system is designed and implemented in the work of Huang, Kuo, Chen, Chang, Wu, and Wu (2009). A tracking mechanism is integrated with an expert controller, sensors and input/output interface, that it can increase the energy generation efficiency of solar cells. In order to track the sun, cadmium sulfide light sensitive resistors are used. To achieve optimal solar tracking, a fuzzy algorithm is developed and implemented. A field programmable gate array is applied to design the controller so that the solar cells always face the sun in most of the day time.

The design and construction of a prototype for solar tracking system with two degrees of freedom, which detects the sunlight using photocells is described in research of Barsoum and Vasant (2010). The control circuit for the solar tracker is based on a PIC16F84A microcontroller (MCU). This is programmed to detect the sunlight through the photocells and then actuate the motor to position the solar panel where it can receive maximum sunlight.

A novel solar tracking scheme which adopts a linear switched reluctance motor (LSRM) as its

servo actuator, is proposed in the research work of Cheung, Zhao, Gan, Sun, Kwok (2008). Three control schemes are designed for different requirements. The solar tracking system is divided into an electromagnetic subsystem and a mechanical subsystem, which are corresponding to the electromagnetic behaviors and the mechanical movement, respectively. The system controller has a cascaded structure, and two different controllers are designed for the two subsystems. Simulation results demonstrate the effectiveness of the modeling and the control scheme.

A solar tracking generating power system is designed and implemented by Huang, Wu, Chen, Chang, and Kuo (2009). An expert controller, sensors and input/output interface are integrated with a tracking mechanism to increase the energy generation efficiency of solar cells. In order to track the sun, cadmium sulfide light sensitive resistors are used. To achieve optimal solar tracking, a fuzzy algorithm is developed. A field programmable gate array is applied to design the controller such that the solar cells always face the sun in most of the day time.

In remote areas the sun is a cheap source of electricity because instead of hydraulic generators it uses solar cells to produce electricity. The output of solar cells depends on the intensity of sunlight and the angle of incidence. It means to get maximum efficiency; the solar panels must remain in front of sun during the whole day. But due to rotation of earth those panels can't maintain their position always in front of sun. This problem results in decrease of their efficiency. Sun tracking systems are very effective in increasing

the efficiency of photovoltaic (PV) arrays, and are essential for concentration PV systems. This experiment discusses a light tracking servo model to simulate the movement of a photovoltaic array. In this experiment a computer simulation program within Matlab is used to simulate the dynamics of the servo system. A qualitative analysis of the Matlab results and the dynamics of the working physical model are compared to clearly illustrate the important dynamics of the system.

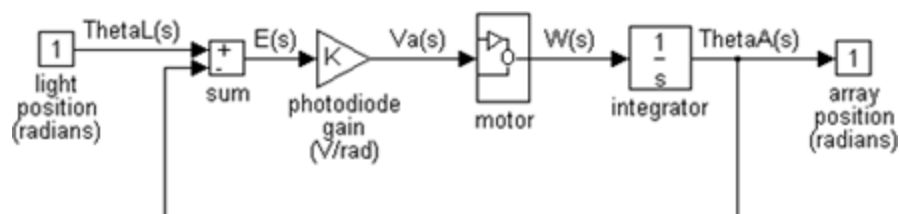
Physical and Conceptual Description

The light tracking system consists of a permanent magnet DC motor, a directional light detecting circuit, and an amplifier to drive the motor. Refer to Figure 1 for the physical configuration and a simple block diagram representation. Two photo sensitive resistors are physically mounted on a triangular Plexiglas mount so that when the panel (the aluminum bar) is perpendicular to the light source, each receives an equal amount of irradiance. When one receives more light than the other, the panel is not aligned properly and an error voltage results. The error voltage is used as a command to an amplifier circuit to drive the motor and align the panel to be perpendicular to the light source beam. The following subsections describe in detail the mechanical and electrical components of the model.

DC Motor

The SRV02 incorporates a MicroMo Coreless DC Motor (2338S006). This model represents a

Figure 1. Block diagram of light tracking servo system



high efficiency low inductance motor resulting in a much faster response than a conventional DC motor. The motor connection is a 4-pin DIN connector configured to be driven by a Quanser Universal Power Module as shown in Figure 2.

Gears

The gears were configured to provide high gear ratio described in Figure 3. This is the recommended configuration for all other experiments that require an additional module such as the ball and beam, gyro, rotary inverted pendulum, etc. This solution is recommended by Quanser since an extra module was attached to the servo plant.

Photoresistor

Photoresistor or light dependent resistor or cadmium sulfide (CdS) cell is a resistor whose resistance decreases with increasing incident light intensity as shown in Figure 4. It can also be referenced as a photoconductor. A photoresistor is made of a high resistance semiconductor. If light falling on the device is of high enough frequency, photons absorbed by the semiconductor give bound electrons enough energy to jump into the conduction band. The resulting free electron (and its hole partner) conduct electricity, thereby lowering resistance.

Photo Detecting Circuit and Amplifier

The light tracking circuit described in Figure 5 provides an electrical driving force to the motor which is proportional to the rotational misalignment of the panels to the light source. This circuit can be broken into three sections; photo detector, gain adjust, and current amplifier.

The photo detector provides a voltage signal which is linearly proportional to the rotational offset from the ideal position of the PV panel. This is accomplished by putting two light sensitive

resistors in an electrical bridge which is connected to a unity gain differential operational amplifier circuit. When one light sensitive resistor receives more light than the other, a differential voltage results across the bridge network which is fed into the op-amp U1A to convert a differential signal into a voltage signal referenced to ground. The photo detecting circuit has a measured gain of approximately 1.6 volts per radian under fluorescent lighting. This gain may vary depending on the intensity of the light.

MODELLING AND SIMULATION OF ELECTRO-MECHANICAL OF A DC MOTOR

The free-body diagram for the rotor is shown in Figure 6. The positive direction is defined as the counter clockwise which is the direction of the T. By applying the Newton's Law the equation can be described as the following:

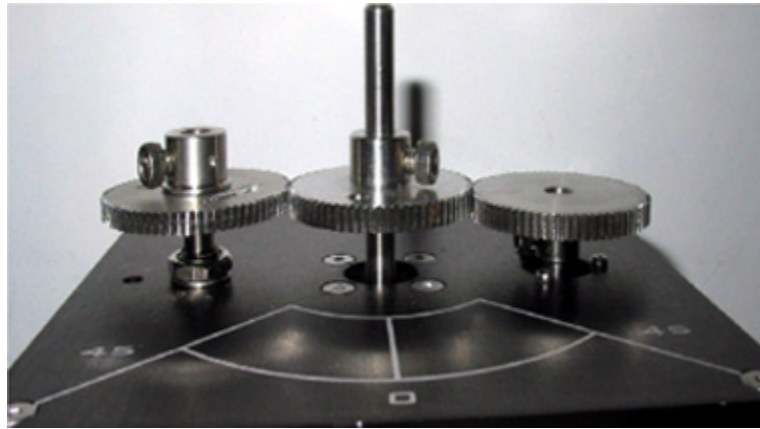
$$\sum F = J_m \ddot{\theta}_m \quad (1)$$

$$J_m \ddot{\theta}_m + b\dot{\theta}_m = T = K_t i_a. \quad (2)$$

Figure 2. DC motor hardware



Figure 3. Gears of the DC drive motor



In Laplace transformation Equation (2) can be written as:

$$(J_m s^2 + b s) \theta_m(s) = K_t I_a(s). \quad (3)$$

Now looking at Figure 6 which represents the electric part of the motor the following equation will be represented by applying KVL:

$$-v_a + L_a \frac{di_a}{dt} + R_a i_a + K_e \dot{\theta}_m = 0. \quad (4)$$

Transforming Equation (4) from the time-domain to the s-domain using Laplace Transformation yields to:

$$(L_a s + R_a) I_a(s) = K_i s \theta_m(s) + V_a(s). \quad (5)$$

Combining the DC Motor mechanical equation part and electrical part, the transfer function will be represented as:

$$\frac{\theta_m(s)}{V_a(s)} = \frac{K_t}{s((J_m s + b)(L_a s + R_a) + K_t K_e)}. \quad (6)$$

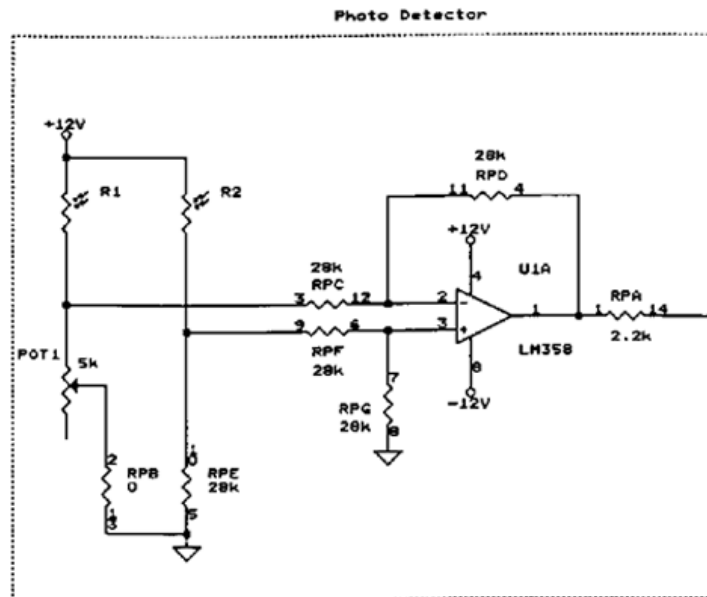
Since inductance can be neglected due to its small value much and has a little effect on the system, then the equation will be represented as:

$$\frac{\theta_m(s)}{V_a(s)} = \frac{K_t / R_a}{s \left(J_m s + \left(b + \frac{K_t K_e}{R_a} \right) \right)} = \frac{K}{s(\tau s + 1)}, \quad (7)$$

Figure 4. The photoresistor



Figure 5. Light tracking circuit diagram for the sun tracker



where the time constant τ and the gain K are defined by:

$$\tau = \frac{J_m R_a}{b R_a + K_t K_e} \quad (8)$$

$$K = K_t / (b R_a + K_t K_e). \quad (9)$$

For the SRV002, the electro-mechanical parameters are listed in Table 1.

Substituting the parameters given in Table 1 in the dynamics equations (7)-(9) yields to the following open-loop transfer function:

$$\frac{\theta_m(s)}{V_a(s)} = \frac{0.0029}{s(2 \times 10^{-3}s + 0.0040)} = \frac{0.7250}{s(0.5s + 1)} = \frac{1.45}{s(s + 2)}. \quad (10)$$

The DC motor open-loop time unit-step response is described in the following Figure 7. It can be seen easily that the open-loop of the system is unstable.

Now, in order to stabilize the system a unity feedback closed-loop circuit should be used as shown in the following block diagram Figure 8. The corresponding unit-step response is demon-

Figure 6. Free Body Diagram of the Electro-mechanical DC Motor Drive

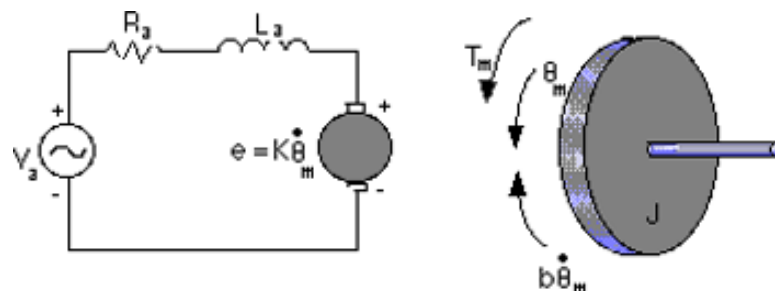
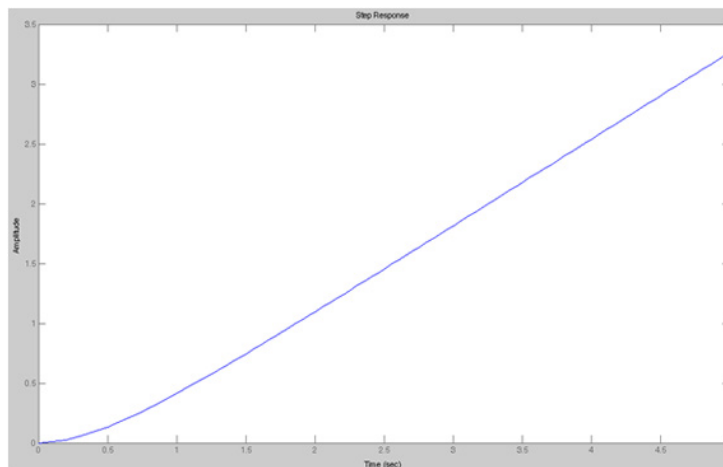


Table 1. DC motor system parameters

Symbol	Name	Value	Units	Variation
K_t	Motor Torque Constant	0.00767	N-m	$\pm 12\%$
K_m	Back EMF Constant	0.00767	V/(rd/s)	$\pm 12\%$
R_m	Armature Resistance	2.6	Ω	$\pm 12\%$
K_{gi}	Gearbox Ratio (Internal)	14:1	N/A	
K_{g-low}	External Low Gear Ratio	1:1	N/A	
K_{g-high}	External High Gear Ratio	5:1	N/A	
J_m	Motor Inertia	3.87 e-7	kg-m ²	$\pm 10\%$
J_{tach}	Tachometer Inertia	0.7 e-7	kg-m ²	$\pm 10\%$
J_{eq-low}	Equivalent Low Gear Inertia	9.3 e-5	kg-m ²	$\pm 10\%$
$J_{eq-high}$	Equivalent High Gear Inertia	2.0 e-3	kg-m ²	$\pm 10\%$
B_{eq-low}	Viscous Damping Coefficient (Low)	1.5 e-3	N-m/(rd/s)	$\pm 20\%$
$B_{eq-high}$	Viscous Damping Coefficient (High)	4.0 e-3	N-m/(rd/s)	$\pm 20\%$
Eff_g	Gearbox Efficiency	0.85	N/A	$\pm 10\%$
Eff_m	Motor Efficiency	0.69	N/A	$\pm 5\%$
K_{pot}	Potentiometer Sensitivity	35.2	Deg/V	$\pm 2\%$
K_{EncE}	Encoder Resolution (E option)	4096	Counts/rev.	
K_{EncH}	Encoder Resolution (EHR option)	8192	Counts/rev.	
K_{tach}	Tachometer Sensitivity	1.5	V/1000RPM	$\pm 2\%$
M_{max}	Maximum Load on Output Shaft	5	kg	
f_{max}	Maximum Input Frequency	50	Hz	
V_{rated}	Rated Motor Voltage	6	V	

Figure 7. Unit-step response of the open-loop DC motor



strated in Figure 9. It is recognized that it takes the system 4 seconds to reach its final value with an error close to zero.

Root Locus of the DC Motor

It is desired now to construct the root locus of the closed-loop DC motor system.

$$G(s) = \frac{1.45K}{s(s+2)}.$$

The zeros and poles of the open loop system are located on the real axis as:

$$\text{Zeros } (m) = \text{None}$$

$$\text{Poles } (n) = s = 0, s = -2$$

The asymptotes point and asymptote angle are calculated as follows:

$$\sigma = \frac{\sum \text{Poles} - \sum \text{Zeros}}{n - m} = \frac{(0 - 2)}{2 - 0} = -1$$

$$\theta = \mp 180(2k + 1) = \mp 90^\circ$$

It is desired now to calculate the break-in and break-away points (if any exist):

$$1 + \frac{K(0.0670)}{s(0.8s + 1)} = 0$$

$$K = -1 \left[\frac{s(s+2)}{1.45} \right] = -[s^2 + 2s]$$

$$\frac{dk}{ds} = [2s + 2] = 0 \quad \text{then } s = -1.$$

Now the root locus of the uncontrolled DC motor can be constructed as shown by Figure 10.

It can be concluded that the closed-loop DC motor system is stable since poles are on the left-half s-plane. But it is interesting to improve the system time response (transient response) using a PD controller as will discussed in the next section.

DESIGN OF A PD CONTROLLER

A proportional–integral–derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems as described in Figure 11. A PID controller attempts to correct the error between a measured process variable and a desired set point by calculating and then outputting a corrective action that can adjust the process accordingly. The PID controller calculation (algorithm) involves three separate parameters; the Proportional, the Integral and Derivative values.

Figure 8. Block diagram of the closed-loop DC motor

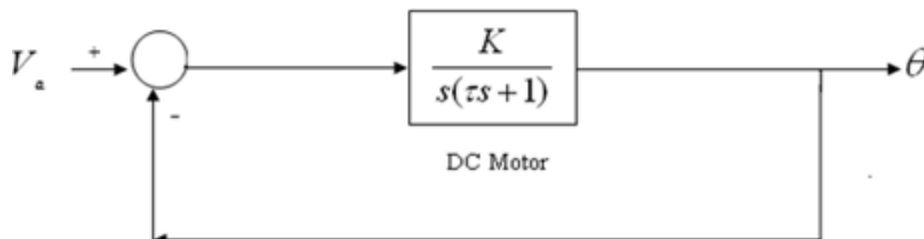
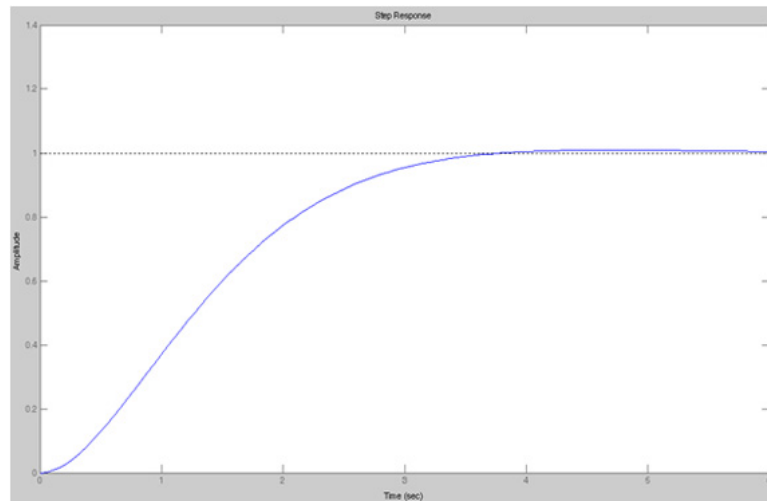


Figure 9. Unit-step response of the closed-loop DC motor

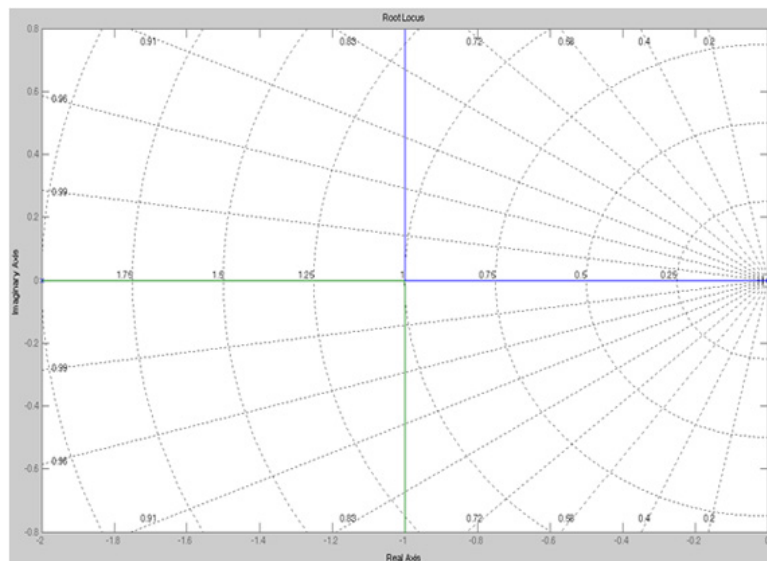


The Proportional value determines the reaction to the current error, the Integral value determines the reaction based on the sum of recent errors, and the Derivative value determines the reaction based on the rate at which the error has been changing. A PID controller will be called a PI, PD, P or I controller in the absence of the respective control actions.

In this chapter only a PD controller is considered for the purpose of design and implementation.. A PD controller is a proportional derivative controller which means that it consists of a proportional coefficient and a derivate coefficient

$$U_{PD}(s) = K_p + K_D s. \quad (11)$$

Figure 10. Root locus of the DC motor system



APD controller is specifically used to improve the transient response of the system. The overall closed-loop PD controlled system now will have the block diagram shown in figure 12.

It is desired to implement an analog op-amp PD controller as demonstrated in Figure 13 with a transfer function modeled by

$$\frac{R_4}{R_3} \frac{R_2}{R_1} (R_1 C_1 s + 1). \quad (12)$$

Note that the addition of a PD controller allows us to deal with the system as a second order system. The standard form of a second order system can be represented as

$$s^2 + 2\xi\omega_n s + \omega_n^2 = 0. \quad (13)$$

where ξ is the damping coefficient of the system, ω_n is the natural frequency of the system. Based on the closed-loop PD controlled system shown in Figure 12, the closed-loop characteristic equation is given as

$$s^2 + \frac{(K_D K + 1)}{\tau} s + \frac{K_P K}{\tau} = 0. \quad (14)$$

where $K_p = \frac{R_4}{R_3} \frac{R_2}{R_1}$ And $K_D = \frac{R_4}{R_3} R_2 C_1$

Design Specifications

The objective now is to design a PD controller such that the overshoot does not exceed 50% and it a settling time of 3 seconds. It is worth to mention that the overshoot and settling time are governed, respectively, by

$$M_p = e^{\frac{-\pi\xi}{\sqrt{1-\xi^2}}} \quad (15)$$

$$t_s = \frac{4.6}{\xi\omega_n} \quad (16)$$

Solving Equations (15) and (16), respectively, for the damping ratio and the natural frequency yields to a damping ratio $\xi = 0.2103$ and natural frequency $\omega_n = 7.29 \text{ rad / sec}$.

Comparing the closed-loop characteristic equation with the standard order second order system leads to a proportional gain and derivative gain values give respectively as $K_p = 36.65$ and $K_D = 0.732$.

Figure 11. A block diagram of a PID controller

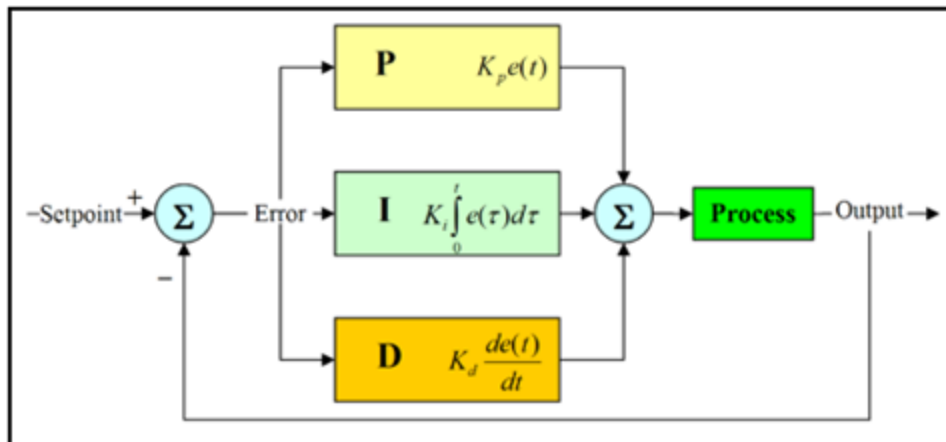
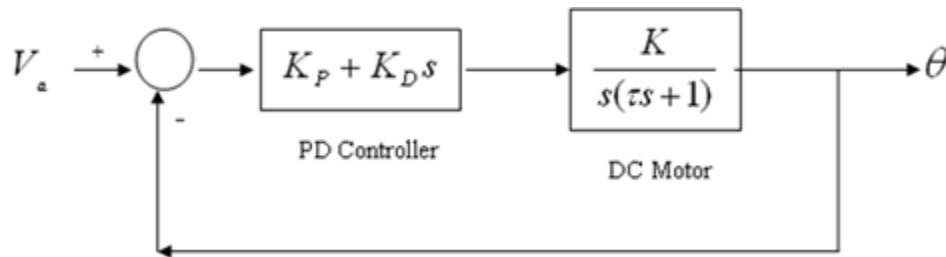


Figure 12. Closed-loop PD controller of a DC motor



Electronic Circuit Design

In order now to design the analog electronic circuit of the PD controller and based on the previous analysis, choose $C_1 = 1\mu F$ and $R_3 = R_4 = 1M\Omega$. Benefiting from $K_D = \frac{R_4}{R_3} R_2 C_1 = 0.732$, and $K_P = \frac{R_4}{R_3} \frac{R_2}{R_1} = 36.65$ then $R_2 = 0.732 M\Omega$ and $R_1 = 20 k\Omega$.

Simulation Results

To verify whether the design of the PD controller has met the desired specifications off-line simulation has been conducted. It is figured out that the design has successfully met the desired specification with overshoot of 51% and a settling time of 2.32 sec as it can be seen in Figure 14. Simulation with Simulink Matlab toolbox has

confirmed the same results as shown in Figure 15 and 16. Moreover, the stability of the system has been also guaranteed as well as demonstrated in Figure 17.

Experimental Results of PD Controlled Systems

Upon completion the modeling and theoretical design analysis and simulation, experimental set up has been conducted for the solar tracking servo system as explained below.

Procedure:

1. Construct the PD op-amp based analog circuit.
2. Connect the photo resistor in the breadboard.
3. Make the connection between the breadboard and the DC Motor.
4. DC Motor and breadboard connected to the UPM 2405 and summer connection.

Figure 13. Based Op-Amp PD Controller

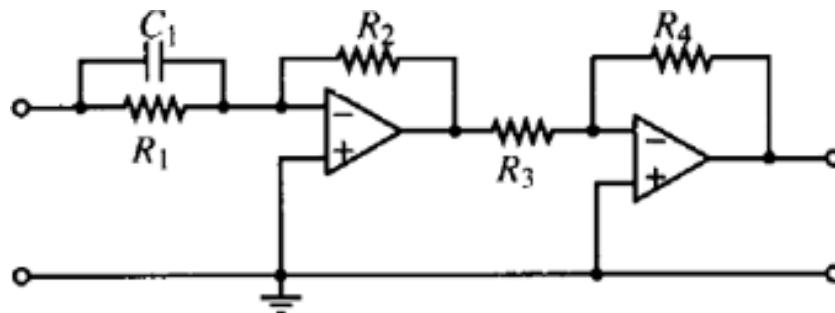
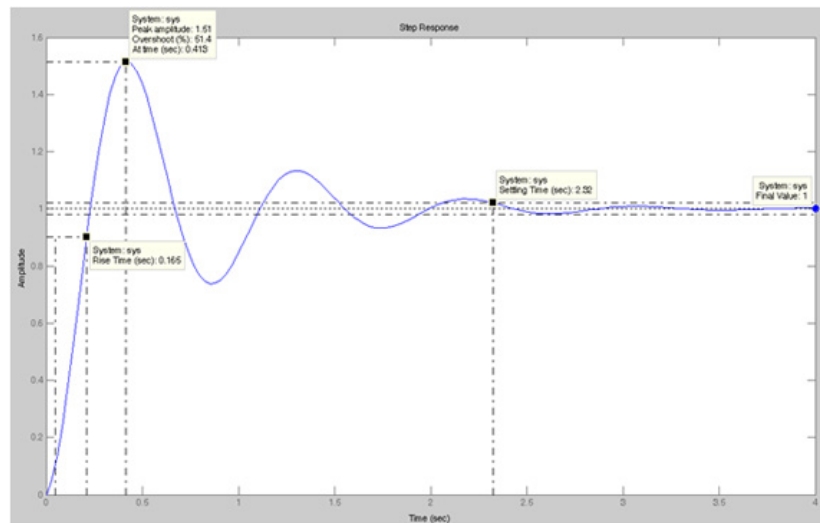


Figure 14. Unit-step response of a closed-loop PD controlled systems



5. Measure the resistors and capacitor values by the DMM.
6. Connect the input and the output of the system to the oscilloscope to visualize the behavior of the system in terms of input-output time performance.

Investigating the system transient response, it is noticed that the system experiences 51.4% overshoot and settling time of 2.3 sec. Consequently, PD controller was able to meet the specifications as demonstrated in Figures 19 and 20.

LAG COMPENSATOR DESIGN

In this section it is required to design a lag compensator without changing the closed-loop poles but it is required to improve the static velocity error constant 20 times as its original value to control the solar tracking controlled system.

Lag compensator is defined as a type of controller that changes the steady state error constant value without changing in the dynamic system characteristics by adding a zero and pole near to the value of zero, where the ratio of the desired error constant and the original one would be the ratio between the zero and the pole of the lag compensator.

Figure 15. System platform using Simulink

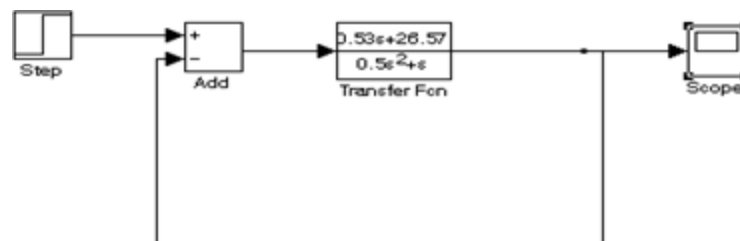
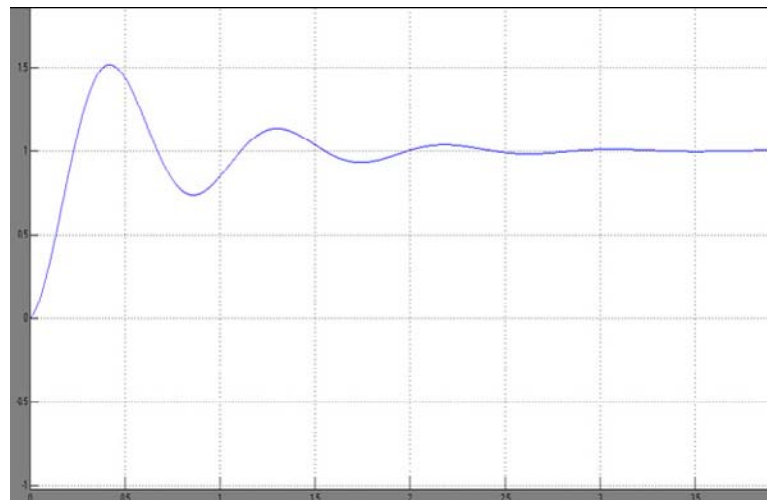


Figure 16. System response using Simulink



Lag Compensator Analysis

Using lag compensator to improve steady state response of the closed loop system, it is required now to calculate for the original velocity static error constant K_{ϑ} such that:

$$K_{\vartheta,original} = \lim_{s \rightarrow 0} sG(s) = \lim_{s \rightarrow 0} s \left(\frac{1.45}{s(s+2)} \right) = 0.725 \quad (17)$$

By the virtue of (17), then K_{ϑ} is calculate as

$$K_{\vartheta,original} = \lim_{s \rightarrow 0} s \left(\frac{1.45}{s(s+2)} \right) = 0.725$$

Since it is specified that the desired velocity static error constant is to be improved 20 times, then

Figure 17. Root locus of the PD controlled system

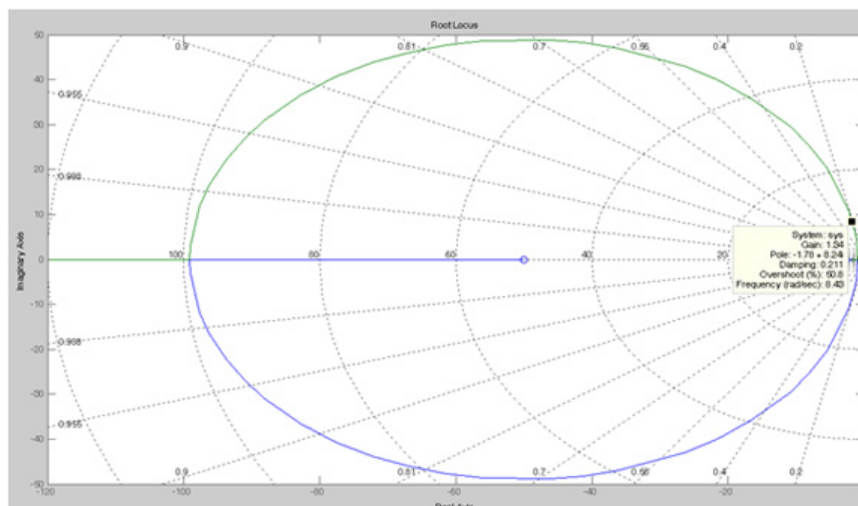


Figure 18. The setup of the light tracking servo system



$$\begin{aligned} k_{\theta \text{ desired}} &= 20 \times 0.725 \\ &= 14.5. \end{aligned}$$

Assume now the compensator zero is selected such that: $Z_c = -0.02$. The attenuation factor $\hat{a}$ can be chosen to have the value 20 (based on the design specifications). The attenuation factor $\hat{a}$ can be defined mathematically as

$$\hat{a} = \frac{Z_c}{P_c}. \quad (18)$$

Based on Equation (18) and the selected value of the zero of the compensator $Z_c = 0.01$, then the pole of the compensator will have the value $P_c = -0.001$

Figure 19. Unit-step response of the experimental results



The objective at the moment is to determine the compensator gain K_c using the desired velocity static error constant given by

$$k_{\vartheta \text{ desired}} = \lim_{s \rightarrow 0} s K_c \left(\frac{s + 0.02}{s + 0.001} \right) \cdot \left(\frac{1.45}{s(s + 2)} \right) = 14.5 \quad (19)$$

which leads to a compensator gain value of unity $K_c = 1$.

For the sake of calculating the values of the resistors and capacitors of the electronic circuit of the lag compensator, the following equations govern the zero, the pole and the gain of the lag compensator, respectively, as

$$Z_c = \frac{-1}{R_1 C_1} \quad (20)$$

$$P_c = \frac{-1}{R_2 C_2} \quad (21)$$

$$K_c = \frac{R_4}{R_3} \cdot \frac{C_2}{C_1} \quad (22)$$

Based on Equation (20), (21) and (22) then

$$R_1 C_1 = 50,$$

$$R_2 C_2 = 1000 ,$$

$$K_c = \frac{R_4}{R_3} \cdot \frac{C_2}{C_1} = 1 ,$$

Choose $R_4 = R_3 = 1M\Omega$ and $C_1 = 1\mu F$, then

$$R_1 = 50M,$$

$$C_2 = 1\mu F,$$

and

$$R_2 = 1G .$$

All the op-amp lag circuit components have been calculated

It is ready now to represent the compensated forward controlled system by the transfer function

$$G_1(s) = \frac{1.45(s + 0.02)}{s(s + 2)(s + 0.001)} . \quad (23)$$

The root locus of the compensated closed-loop controlled system can be demonstrated using Matlab as shown in Figure 22.

Next section will provide the experimental details of the lag compensator set-up.

Experimental Results of the Lag Compensator

1. Construct the op-amp analog circuit as shown in figure (21) such that $R_4 = R_3 = 1M\Omega$ and $C_1 = 1\mu F$, then $R_1 = 50M\Omega$, $C_2 = 1\mu F$ and $R_2 = 1G\Omega$. The bread board of lag compensator is built as in Figure 23.
2. Connect the constructed Lag controller circuit with Analog System Control (ACS) as in Figure 24.
3. Connect ACS with DC motor as in Figure 25.
4. Upon completing connecting Lag control circuit with ACS, oscilloscope and DC motor, connect the Lag circuit with DC generator and signal generator described in Figure 26
5. Adjust input voltage amplitude and offset

Figure 20. Error response of the experimental results

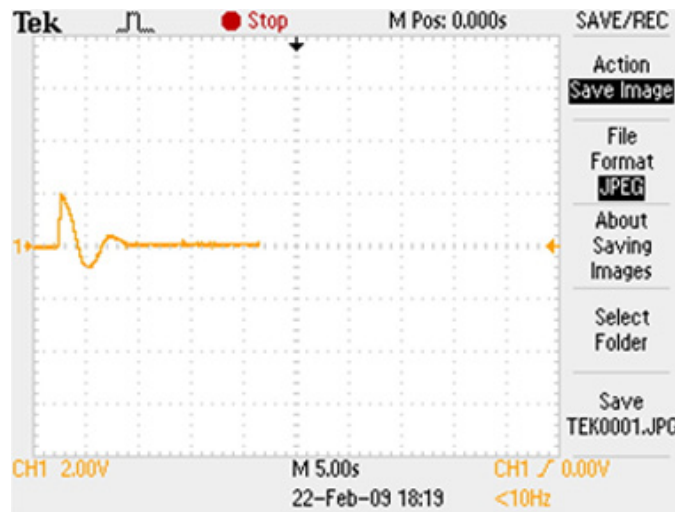


Figure 21. Op-amp lag compensator circuit

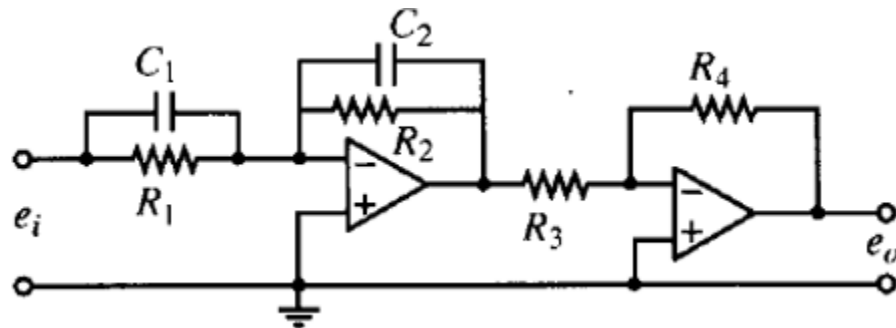


Figure 22. Root locus with the lag compensator

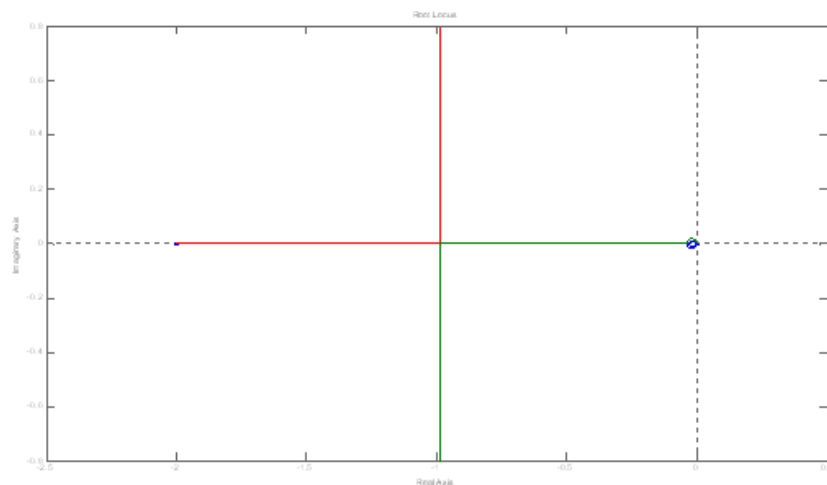


Figure 23. Constructed lag compensator circuit on the bred board

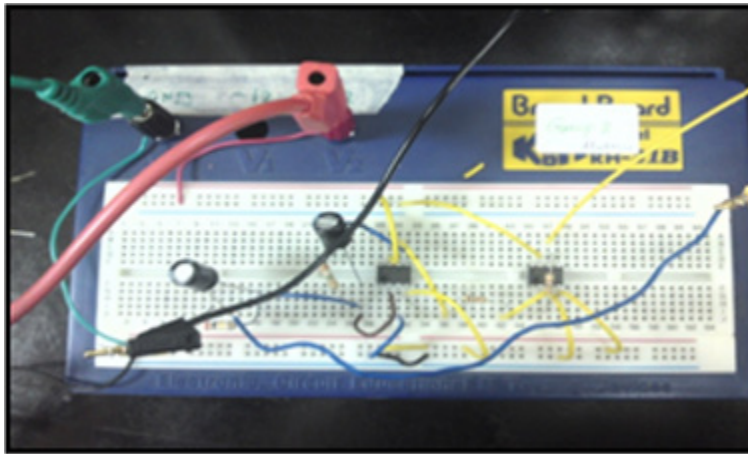
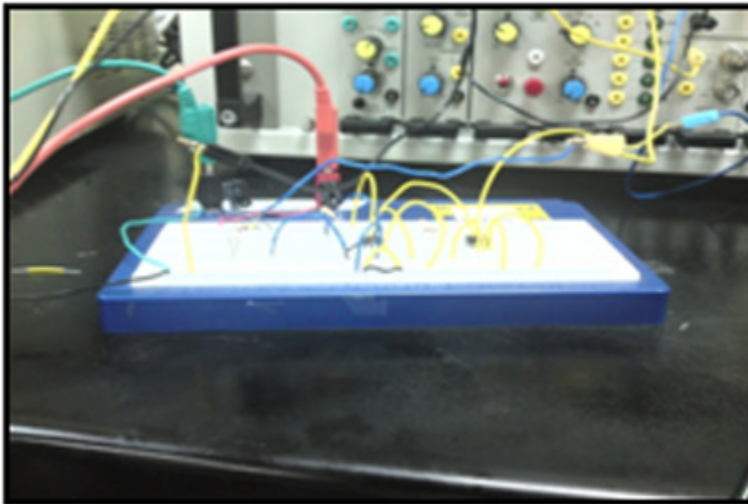


Figure 24. Lag controller circuit connected to ACS



6. Using oscilloscope demonstrate and record the result of the system response and the steady state error.

Figures below shows the results for the lag compensator, the steady state response was improved against transient response as shown in Figure 27. The steady state response of the system was very fast and there is no overshoot. In addition, the steady state error is still valid but it reduces from the original value. The error signal is

stable else. Although from the origin, the system was unstable but after awhile it change to be stable as displayed in Figure 28.

DISCUSSION AND CONCLUSION

Horizontal axis sun tracking system which is proposed in this chapter is able to track the sunlight. Compared with fixed-position installations, solar tracking systems make solar energy a viable

Solar Photovoltaic Servo Tracking Controlled System

Figure 25. Connected ACS to the DC motor

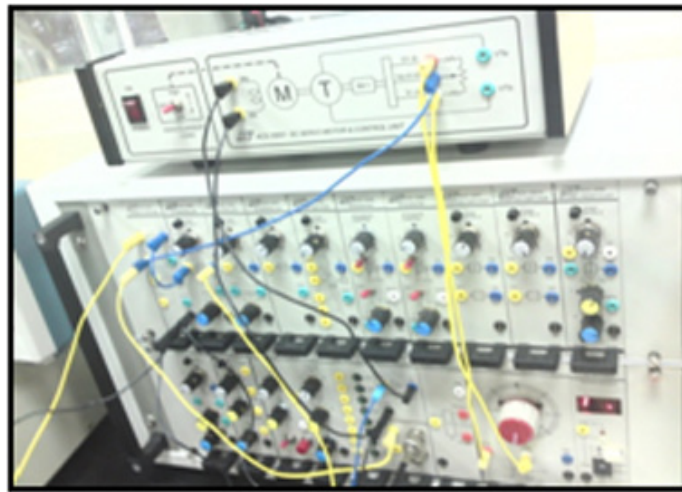


Figure 26. Connected ACS, DC motor, and lag compensator circuit

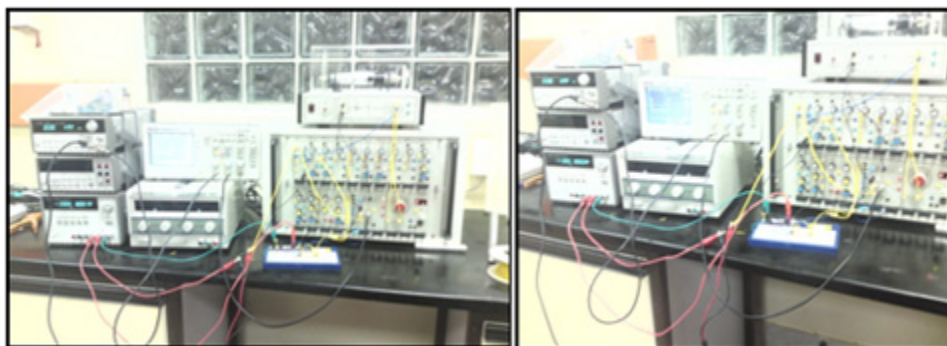


Figure 27. The steady-state response feedback signal with step input

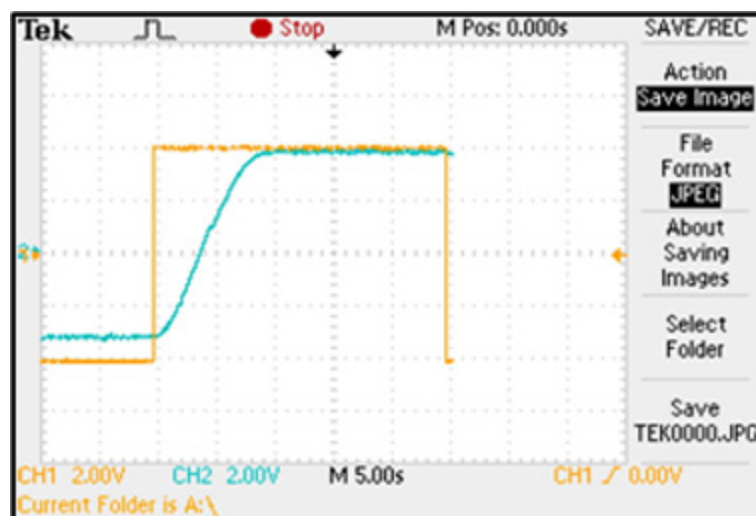
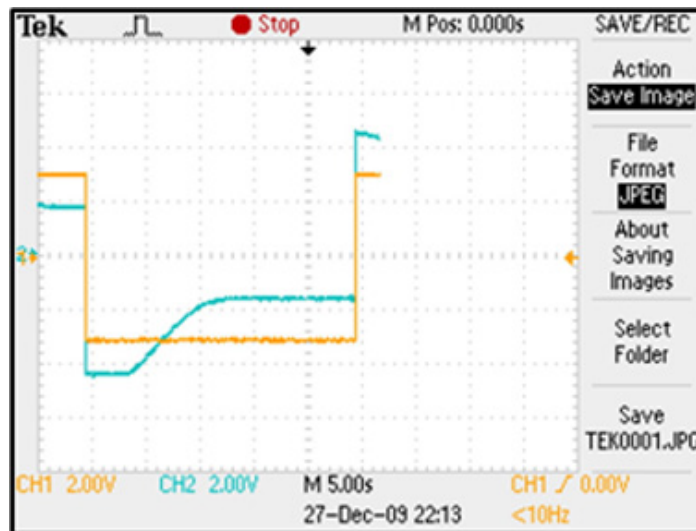


Figure 28. The error signal with step input



long-term option to other energy sources. Such a system is recognized by its low cost and easiness to implement. It is known that optimal energy is obtained when the rays of the sun are incident normally on the collecting surface. Therefore, solar panel tracking systems energy output of photovoltaic panels can be optimized by positioning them to follow the sun's path throughout the day. The sun's position in the sky varies both with installation location, the seasons, and the time of day.

The minimum sun tracking error is achieved using an electro-optical DC motor and PD controller as well as a lag compensator. Remarkably, it can be easily implemented using phototransistors which are mounted on the solar panel and placed in an enclosure to inform the PD controller on the required orientation of the solar panel.

In this chapter a control method is proposed for the control of a sun servo tracker. In particular, two control algorithms have been presented in order to improve the tracking time response. The design of the proposed controller is simple because it is based on the well-known and easy-to-use op-amp PD controller and lag compensator.

The obtained simulation results are quite encouraging; they show the efficiency and the simplicity of the proposed method. The most important advantage of our method is the short overshoot time to track the light.

At this stage, our efforts are focused on one-axis control output. This is motivated by the avoidance of three DC motors. Future work is to pursue research work by controlling two or three axes solar tracking system. The adequate criterion for the solar tracking control can be improved real-time computer controlled system.

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KEY TERMS AND DEFINITIONS

Analog Operational-Amplifier: A high gain electronic voltage device used to amplify a DC input voltage.

DC Motor: An electrical motor that operates on direct electric (constant) current.

Lag Compensator: Is an electronic device used in control systems to improve the system frequency response.

Matlab: Is trademark software that uses a high-level language and interactive environment that enables a user to perform computational tasks faster than with traditional programming languages.

PD Controller: A proportional–integral–derivative controller (PID controller type) is used in control systems based in calculation the error value as the difference between a measured value and reference value.

Photoresistor Cell: Is a resistor whose resistance decreases with increasing incident light intensity.

Renewable Energy: Is the energy produced from natural resources such as sunlight, wind, waves and geothermal heat.

Root Locus: Is a graphical tool used in control systems to examine how the roots of a system is changed by varying the system parameters.

Solar Photovoltaic Servo Tracking Controlled System: A system in which a photovoltaic panels is controlled to follow and track the sunlight so as to increase its output and efficiency.

Time Response: How and how long it takes a generic system to react to a given input.

Chapter 4

Power Electronics and Controls in Solar Photovoltaic Systems

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ABSTRACT

The use of renewable energy sources is increasingly being pursued as a supplemental and an alternative to traditional energy generation. Several distributed energy systems are expected to have a significant impact on the energy industry in the near future. As such, the renewable energy systems are presently undergoing a rapid change in technology and use. Such a feature is enabled clearly by power electronics. Both the solar-thermal and photovoltaic (PV) technologies have an almost exponential growth in installed capacity and applications. Both of them contribute to the overall grid control and power electronics research and advancement. Among the renewable energy systems, photovoltaic (PV) systems are the ones that make use of an extended scale of the advanced power electronics technologies. The specification of a power electronics interface is subject to the requirements related not only to the renewable energy source itself but also to its effects on the operations of the systems on which it is connected, especially the ones where these intermittent energy sources constitute a significant part of the total system capacity. Power electronics can also play a significant role in enhancing the performance and efficiency of PV systems. Furthermore, the use of appropriate power electronics enables solar generated electricity to be integrated into power grid. Aside from improving the quality of solar panels themselves, power electronics can provide another means of improving energy efficiency in PV and solar-thermal energy systems.

INTRODUCTION

This chapter will discuss current developments in the controls and power electronics that enable the PV systems to become a real power source for the grid system. In the last decade, the PV power supplied to the utility grid has been gaining more and

more visibility due to several reasons. First, there have been considerable incentives for developers, second, there have been technology advances, and finally, both fuel prices and environmental concerns have pushed the interest forward. Power electronics and control technologies will play a key role in changing the characteristics of a renewable

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energy system to an active power source in the near future. The expected trends in power electronics and control technologies for solar energy systems are also discussed in this chapter.

Renewable energy systems are presently undergoing a rapid change in technology and use. This rapidly growing interest in various aspects of clean energy is a reaction to the major energy-related challenges of the humanity. These efforts involve renewable energy sources, distributed generation systems, and conservation of energy in a variety of the electromechanical energy systems such as industrial drivers, electric and hybrid cars, etc. The renewable energy systems (RES) are now a major contributor to the grid power. In classical power systems large power generation plants located at adequate geographical places produce most of the power, which, is then transferred to the large consumption centers over long distance transmission lines. The system control centers monitor and regulate the power system continuously to ensure the quality of the power, namely frequency and voltage. However, now the overall power system is changing and a large number of dispersed generation (DG) units, including both renewable and non-renewable sources such as wind turbines, PV generators, fuel cells, etc. are being developed and installed. Solar energy alone has an almost exponential growth in installed capacity and applications in the last three decades. A widespread use of the renewable energy sources in distribution networks and a high penetration level will be seen in the near future in many places. To interface a renewable energy source efficiently to a load or grid the power electronic converters are performing power conditioning, voltage boosting, power flow control and power quality improvements.

Power electronics has changed rapidly during the last decades and the number of applications has been increasing mainly due to the development of semiconductor devices and microprocessor technology. For both, higher performance has been steadily increasing for the same area of

silicon, while at the same time, price has been continuously reducing. Power electronics, being the technology of efficiently converting electric power, plays an important role in the field of modern electrical engineering. It is an essential for the integration of the DG units in order to achieving high efficiency and performance. A power converter is the interface between a generator and the load or the grid. For most of the power converters, the power may flow in both directions, though this is dependent upon topology and applications. Three important issues are of concern using such systems, the reliability, the efficiency and the cost. In the last decades, the trends are that power electronic conversion is shrinking in volume, size and weight. It has also been shown that more integration and functions that are more available are the keys to being competitive. The key driver of this development is the advances in the device technology.

This chapter presents several examples of power electronics and control applications in the PV/solar energy systems, both utility interactive systems and stand-alone systems. The most common power electronics topologies and control strategies for photovoltaics are discussed in details. PV systems can be classified as follows: a) Stand-alone PV Systems; b) Hybrid Power Systems; and c) Grid Connected or Integrated Systems. Each type of system generally requires a power electronics interface unit to enable the PV system to transfer solar cell generated electricity optimally to the desired load, grid or storage system. Power electronics and control units for PV systems are of two types: stand-alone and grid-connected. The two types have several similarities but they are different in terms of control functions. The intent of this chapter is to present the *what*, *why* and *how* of PV system control, power electronics and design. The use of power electronics in PV system is described in details. Conversion, control and monitoring of electric energy with the use of semiconductors are also described. Methods for analyzing convert-

ers including resonance converters for design are presented in detail. Selection of converter topologies is included in this chapter. One section of the chapter is dedicated to the modular power electronics concepts, control techniques, and their applications in renewable energy technologies, and especially for the photovoltaic (PV) systems. Different power electronics topologies are discussed for each of the PV systems and the advantages and disadvantages of generalized topologies were presented for understanding the control design.

POWER ELECTRONIC CONVERTERS FOR PHOTOVOLTAICS

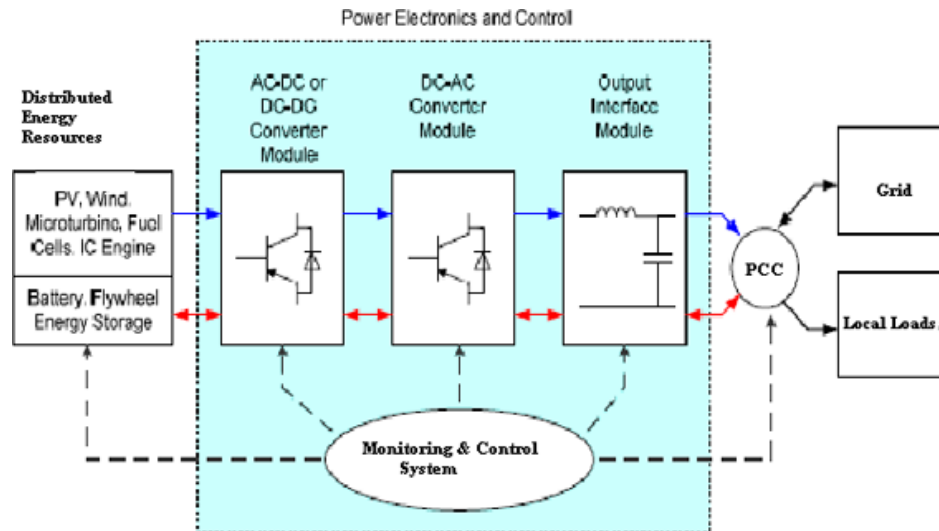
Power electronic circuits are key elements for renewable energy power generation. The power electronics for solar power conversion shall have the ability to automatically track the maximum power point (MPP) in order to achieve the maximum efficiency of the solar cells and inject sinusoidal and in-phase current to the grid so that power quality complies with the power system requirements. Figure 1 shows a general block diagram of general power electronics interface for use with DES systems and can be subdivided into four major modules. These include: the source input converter module, an inverter module, the output interface module, and the controller module. The blue arrows depict the power flow path for the RES sources whereas the red arrows show the bidirectional power flows for the RES storages. The input converter module can be either used with alternating current (AC) or direct current (DC) RES and is most likely to be specific for each type of energy source or storage device. The DC-AC module (inverter) is the most generic of the modules and converts a DC supply to a grid-compatible AC power. The output interface module filters the AC output from the inverter. The fourth major module is the monitoring and control unit that operates the entire interface and

contains protection for both the DES source and the utility at the point of coupling. Due to many inherent similarities in these modules, it is possible that a modular and scalable power electronics interface could allow each of the energy source technologies to use the same power electronic components within their system architectures. These requirements can lead to modular and flexible design of the power electronics converters for the DES&DG applications.

A power electronic converter is an electronic system for converting and controlling electric energy (current, voltage, and frequency) designed to supply a load. The power converters apply one or more switching power semiconductor, magnetic components, capacitors, control electronics and other essential supplementary components. Power electronic converters are found in a countless number of applications in a very wide range of power and circuit topologies. In order to make the power generated by PV systems useful especially for grid-tied applications, it must be converted to AC, via inverters. Inverter generate a regulated AC supply from a DC input, and are commonly found in systems providing standalone AC power, utility-connected DES systems, or at electric motor control. There also are a significant number of applications for the DC-DC converters in PV and solar energy systems. They are used to convert the DC voltage magnitude from one level to another for a specific load application, with or without galvanic isolation. An example for such topology can be found in PV applications, where the dedicated DC-DC units are often designed to extract the maximum power output of the PV array. A summary of the different power converters that can be used for DES applications are given in Shepherd and Zhang 2004, Teodorescu et al., 2011, or elsewhere in the literature. A bloc diagram of a typical power electronic converter is shown in Figure 2.

There are four main classes of power electronic converters: a) AC-DC converters (rectifiers) that convert an input AC to a DC signal with adjust-

Figure 1. Modular configuration for RES power electronics interface. Block diagram of typical RES power electronic systems. Adapted from Kramer et al. 2008.

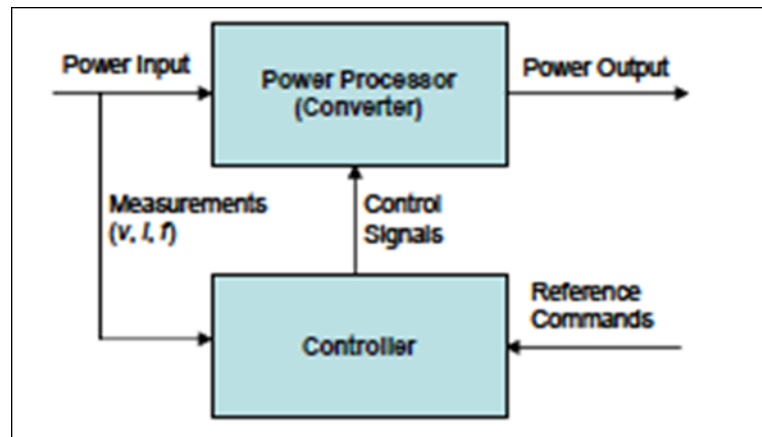


ment of output voltage and current; b) DC-AC converters (inverters) that produce an output AC voltage of a controllable magnitude and frequency from an input DC voltage; c) AC-AC converters (cycloconverters) that change AC frequency, phase, magnitude, and shape; and 4) DC-DC converters (choppers) that change the DC voltage and current levels (Mohan et al. 2003). Each of these converters consists of the primary electronic elements: resistors, capacitors, transformers, inductors, etc., and basic semiconductor devices: a) diodes, including Zener, and Schottky diodes, and diacs; b) thyristors, particularly silicon-controlled rectifiers (SCR), triacs, gate turn-off (GTO), and MOS-controlled thyristors; and c) transistors, such as bipolar junction (BJT), field-effect (FET), and insulated gate bipolar (IGBT) transistors. To facilitate the design and simplify the physical layout of the power electronic converters, manufacturers offer a variety of *power electronic modules*, representing a set of power switches interconnected into a specific topology and enclosed in a single case. Most popular topologies are single- and three-phase bridges or their subcircuits. Power electronic modules

may also contain several switches of the same type connected in series, parallel or series-parallel, to increase overall voltage and/or current ratings.

A solar cell is the core of PV technology, and is typically made of semiconductor materials such as crystalline silicon and absorbs sunlight and produces electricity through the photovoltaic effect. The efficiency of a solar cell is determined by its ability to convert available sunlight into usable electrical energy and is typically around 10%-15%. Therefore, to produce significant amount of electrical energy, the solar cells must have large surface areas. Individual solar cells are usually manufactured and combined into modules that consist of 36 to 72 cells, depending on the output voltage and current of the module. The modules vary in size by manufacturer, but are typically between 0.5 to 1 m² and generate around 100 W/m² of energy during peak solar conditions for a 10% efficient module (Blaabjerg et al. 2004, Messenger and Ventre, 2010). The modules may also be grouped together in various configurations to form arrays with specific voltage and current characteristics. The distinction between

Figure 2. Block diagram of a power converter



modules and arrays is important when considering power electronics interfaces, as power electronics manufacturers design their products using either module-centric or array-based approaches. The magnitude of the voltage output of a PV system depends on the configuration in which the solar cells/modules are connected. On the other hand, the current output from the PV system primarily depends on the available solar irradiance. The main requirement of power electronic interfaces for the PV systems is to convert the generated DC voltage into a suitable AC for consumer use and utility connection. Generally, the DC voltage magnitude of the PV array is required to be boosted to a higher value by using choppers before converting them to the utility compatible AC. The inverters are then utilized to convert the voltage to 60/50 Hz AC. The process of controlling the voltage and current output of the array must be optimized based on the weather conditions. Specialized control algorithms have been developed called maximum power point tracking (MPPT) to constantly extract the maximum amount of power from the array under varying conditions (Blaabjerg et al., 2004, Iov et al., 2010). The MPPT control process and the voltage boosting are usually implemented in the DC-DC converter, whereas the inverter is used for grid-current control (Blaabjerg et al., 2006 and 2010, Kroposki, 2010).

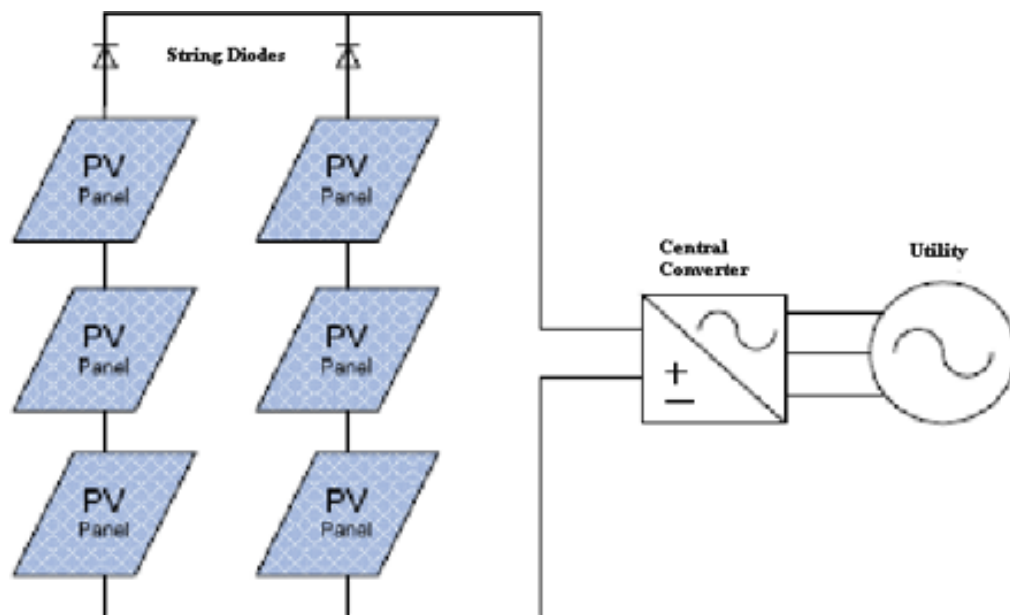
The PV inverter is the key element for PV systems performing several functions. It converts the generated DC power into AC power compatible with the utility. It also contains the protective functions that monitor grid connections and the PV source and can isolate the PV array if grid problems occur. The inverter also monitors the terminal conditions of the PV module(s) and contains the MPPT for maximizing the energy capture. The MPPT maintains the PV array operation at the highest possible efficiency, over a wide range of input conditions that can vary due to the daily and seasonal variations (Blaabjerg et al., 2004, 2010, Iov et al., 2010). PV Systems can be structured into several operational configurations. Each configuration has the basic power electronic interfaces that interconnect the system to the grid or to a load. Figure 3 shows the configuration where a centralized inverter is used. This has been the most common type of PV installation configuration with less use in today applications, except for the large PV plants. In this configuration, PV modules are connected in series and/or parallel and connected to a centralized DC-AC converter. The primary advantage of this design is the fact that if the inverter is the most costly part in the installed PV system, this system has the lowest cost design because of the presence of only one inverter. The primary disadvantage of this configuration is that

the power losses can be high due to the mismatch between the PV modules and the presence of string diodes (Blaabjerg et al., 2004 and 2006). Another disadvantage is that this configuration has a single point failure at the inverter; therefore, it has less reliability (Kjaer et al., 2005).

Central inverters are one of the most common power electronics interface used in PV systems today. In this model (Figure 3), a single, large inverter is connected to many PV modules wired in series to form strings with up to 600V of open-circuit voltage (1,000V in Europe). Multiple strings within the array may also be wired together in parallel before converging at the inverter, yielding some added flexibility in system design and performance. The efficiency of many central inverters is 95% or higher, and they feature a relatively low unit cost per watt (Kjaer et al. 2005, Teodorescu et al. 2011). However, central inverters have multiple drawbacks. They perform maximum power point tracking on the combined DC voltage and current produced by the series-connected modules, resulting in lost energy harvest due to module mismatch and varying shading

conditions across the array. The use of high-voltage DC wiring raises some safety concerns, such as a higher risk of arc faults, which is a primary cause of PV-related fires. Central inverters cannot monitor the performance of individual PV modules, so damaged or otherwise compromised modules often go undetected. Central inverters also necessitate additional installation and system design costs, and a failure of the inverter results in a complete loss of production from the entire array. Central inverters usually carry five- to ten-year warranties, such a system-level outage can occur several times over the operating life of a PV system, and leads to the costly purchase and installation of a replacement inverter each time. Finally, central inverters limit the design and site selection of the PV systems, particularly in residential or low-power applications. They require co-planar module layouts and a lack of partial shading from chimneys, trees, vent pipes, etc. PV installers may out of half or more of potential sites due to these restrictions.

Figure 3. Centralized PV system configurations



PHOTOVOLTAIC SYSTEM MODEL, SOLAR CELL EQUIVALENT CIRCUIT

Solar generators deliver DC voltage or current. Some of the small appliances (such as watches and computers) are designed for DC supply, while most of the appliances require AC current of 230/120 V and a frequency of 50/60 Hz to operate. Even, for stand-alone PV systems without grid-connection, frequently power conditioning and inverters are used to convert DC current into appropriate AC power required by commercially available appliances. However, the inverters are required to convert the PV generator electricity into similar electricity of the grid. The output of the inverter can be single- or three-phase voltage system. Inverters are rated by the total output power capacity, which ranges from hundreds of watts to megawatts. The designers should specify both the type and the size of the load the inverter is intended to service. An inverter is also characterized by its power-dependent efficiency. Another main function of an inverter is to keep a constant voltage on AC side and convert the input power into the output power with highest possible efficiency. Due to advances in semiconductor device technology, the inverter topologies have changed, in the last decades from large thyristor-equipped inverters to smaller IGBT-equipped ones, permitting to increase the switching frequency in order to extract more energy and fulfill the connecting

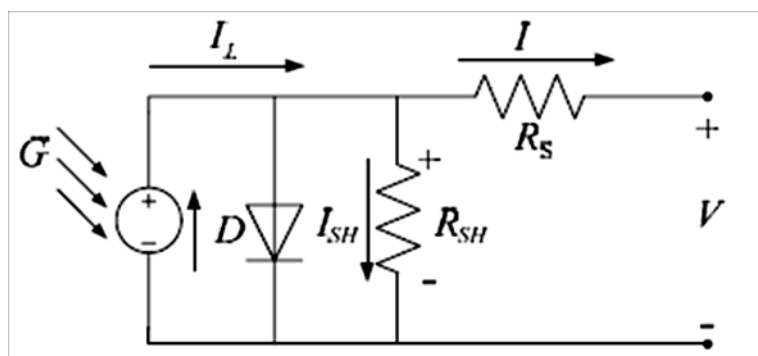
standards. One requirement of standards is that the inverters must also be able to detect an islanding situation and take appropriate measures in order to protect persons and equipment (Myrzik and Calais, 2004, Carrasco et al., 2006).

Solar cells are the building blocks of the PV systems designed to convert solar energy into electricity. A solar cell is a p-n semiconductor junction, when exposed to light a DC current is generated. The generated current varies linearly with the solar irradiance. The standard equivalent circuit of the PV cell is shown in Figure 4. The basic equation that describes the I-V characteristics of the PV model is expressed as:

$$I = I_L - I_0 \left(\exp \left(\frac{q(V + IR_s)}{kT} \right) - 1 \right) - \frac{V + IR_s}{R_{SH}} \quad (1)$$

Here: I is the cell current (A); I_L is the light generated current (A); I_0 is the diode saturation current; q is the charge of electron = 1.6×10^{-19} (C); k is the Boltzman constant (J/K); T is the cell temperature ($^{\circ}\text{K}$); R_s , R_{sh} are cell series and shunt resistance (ohms); and V is the cell output voltage (V). A typical PV system model is made up of the following components: PV array, MPPT controller, battery charge controller, batteries, critical loads, and/or non-critical loads. PV arrays generally range in efficiency from 6% to 30%, with

Figure 4. Equivalent circuit of a solar cell



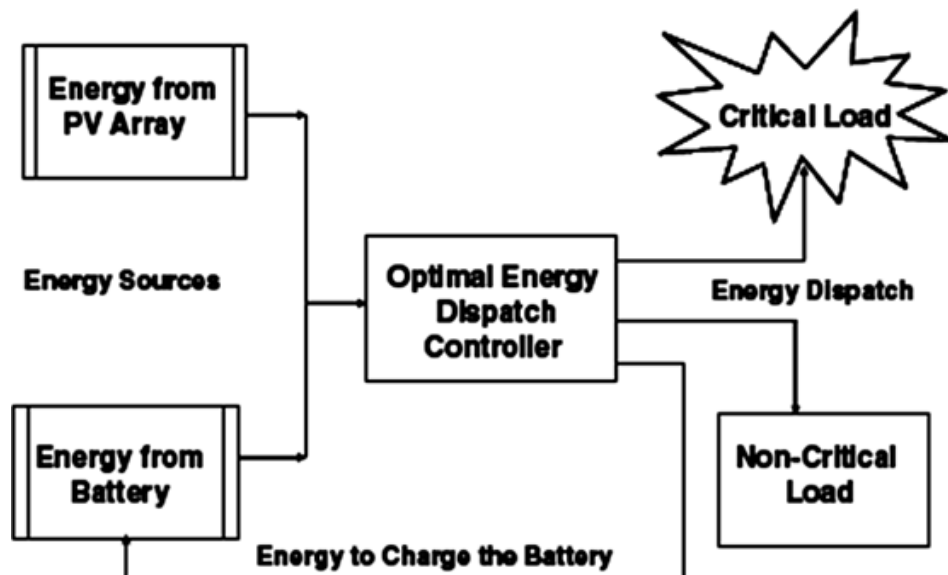
costs varying tremendously. Usually, the 30% efficiency arrays are used for space applications because of their power generation density (and radiation tolerances), while arrays with 6% to 15% efficiency are used for typical terrestrial applications. A block diagram of this PV system setup is shown in Figure 5.

The main drawbacks of PV system technologies are high fabrication cost and low energy-conversion efficiency, which are partly caused by their nonlinear and temperature-dependent current-voltage (I-V) and power-current (P-I) characteristics. Three essential approaches are used to overcome these drawbacks: 1) improving the manufacturing processes of the solar arrays (Benner and Kazmerski, 1999; Messenger and Ventre, 2010); 2) controlling the insolation input to PV arrays, the input solar energy is maximized using sun-tracking solar collectors (Riatsch et al., 1997; Shimazu et al., 2001; Salas et al., 2006) or rearranging the solar-cell configurations of PV arrays with respect to changes in environmental conditions (Watanabe et al., 1998; Calais et al., 2000); and 3) utilization of output electric power of solar arrays. The main reasons for the low electrical

efficiency are the nonlinear variations of output voltage and current with solar radiation levels, operating temperature, and load current. To overcome these problems, the maximum power operating point of the PV system (at a given condition) is tracked using online or offline algorithms and the system operating point is forced toward this optimal condition (Salas et al., 2006; Mutoh et al., 2006; Femia et al., 2008; Gules et al., 2008; Blaabjerg et al., 2010).

Over the years, many MPPT techniques have been proposed, analyzed, and implemented. They can be categorized as: a) “Look-up table” methods, b) “Perturbation and observation (P&O)” methods, and c) “Computational” methods (Salas et al., 2006, and 2009). The nonlinear and time-varying nature of solar cells and their great dependency on radiation and temperature levels as well as the degradation (aging, dirt) effects, make it difficult to record and store all possible system conditions, making the first MPPT category difficult to apply. On the other hand, the measured cell characteristics (current, voltage, power) are employed, in the P&O methods along with an online search algorithm to compute the corresponding

Figure 5. Block diagram of the PV system model



maximum power point independent of insolation, temperature, or degradation levels. Problems with this approach are the undesirable measurement errors (especially for current) which strongly affect tracker accuracy. In the last MPPT methods, the nonlinear I-V characteristics of the solar panel are modeled using mathematical equations or numerical approximations. The model must be valid under different insolation, temperature, and degradation conditions. Based on the modeled I-V characteristics, the corresponding maximum power points are computed for different load conditions as a function of cell open-circuit voltages or cell short-circuit currents.

One of the major disadvantages previously associated with the applications of PV power generation, such as initial cost, efficiency, and reliability, no longer present such a significant problem, due to the unprecedented advances in PV technologies over the last three decades. Today, the PV generation is a flexible power generation technology, applicable in both small and large power generation plants (anywhere from less than 3 kVA to over 100 kVA). In recent years, there is an increased interest in the small PV power generation systems designed to be installed and used in the house. However, various problems limit the effectiveness and economic feasibility of PV power generation. When a typical urban home is equipped with a PV power generation system the PV modules are normally installed on the roof. Thus, in addition to shadows created by clouds, those created by neighboring homes, trees, utility and/or telephone poles, and power line cables sometimes partially cover these PV modules. These factors may lower the overall generated power to a larger degree than was initially expected. Thus, the construction cost is increased, because the number of PV modules installed on the roof must be increased, and as a result, PV power generation will be less attractive. Therefore, new power electronic circuits were designed and developed to generate the maximum power for each of the modules, or PV configurations. As a

result, the decrease in the total generation power is minimized (Shimazu et al., 2001; Femia et al., 2005, 2006 and 2007; Kerekes et al., 2007; Salas et al., 2009). The generation control circuits enable each of the individual PV modules to operate effectively at maximum power even when some of the PV modules are covered by shadows.

PV INVERTER CONFIGURATIONS AND TOPOLOGIES

The PV power generators, the array of solar cells, may be configured in many ways, and accordingly, the DC to AC power conversion as well (Wilk, 1995). From single modules with individual inverters, over strings of modules with associated inverter, to large arrays of serial and parallel connections of modules, with one or more (e.g. configured in master-slave mode) central inverters; many different configurations and topologies may be applied. Functionalities that need to be covered include: 1) converting DC power into AC power with highest possible efficiency; 2) tracking the PV array's maximum power point with highest possible static and dynamic accuracy; 3) sinusoidal waveform of the output current proportional to the grid voltage and lowest possible harmonics produced; and 4) safety functions, surveillance and protection from DC side faults and AC side grid irregularities, including monitoring of voltage and frequency and consequent stopping of power delivery in case of irregularities (to avoid undesired islanding). Nowadays, technical improvements and advances in the circuit design of the converters, and integration of the required control and protection functions into the converter control circuit have allowed introducing into the market advanced PV converter systems that also provide sufficient control and protection functions such as maximum power tracking, inverter current control, and power factor control. Within the range of power until 10 kW several DC-AC converter configurations have been proposed

from single stage to double or multi-stage topologies according to the number of cascaded power stages, with or without a low or high frequency power transformer. Single-stage single-phase or three-phase inverters are the traditional solution adopted to interface a large number of PV modules to the grid as the modules are connected in series to create strings with a suitable high value of the output voltage and the strings are connected in parallel through interconnection diodes to obtain the desired power level.

The presence of the low-frequency transformer and the poor efficiency of the centralized inverter associated to the poor performance of the MPPT, have moved to “string conversion” solutions, which basically consist in a double stage power converter for each string of the PV plant. Using an input stage in boost configuration allows one to connect fewer panels in series to create the DC voltage, while increasing the overall efficiency of the power conversion, as the blocking diodes are not requested and the MPPT algorithm is applied to only one string with limited number of panels. String conversion configurations based on several DC-DC converters connected to a high voltage DC bus and linked to a single DC-AC converter in principle appear as more complex solutions but offer higher efficiency due to single string MPPT control and modularity of the PV plant. Finally, for very low-power applications it is recognized that the solution based on AC modules is the best one to solve such issues as input power optimization, plant modularity, and system reliability. With this architecture every single PV panel is directly connected to the grid through micro-inverters (MIC) having the same power of the panel and installed on its back side. Depending on the PV system configuration, according to Teodorescu et al., 2011, the PV inverters can be categorized as:

1. Module integrated inverters, typically in the 50-400 W range for very small PV plants (usually a single panel).
2. String inverters, typically in the 0.4-2 kW range for small rooftop plants with panels connected in one string.
3. Multi-string inverters, typically in the 1.5-6 kW range for medium large rooftop plants with panels configured in one or two strings.
4. Mini central inverters, typically > 6 kW with three-phase topology and modular design for larger rooftops or smaller power plants in range of 100 kW and typical unit size of 6, 8, 10 and 15 kW.
5. Central inverters, typically in the 100-1000 kW range with three-phase topology and modular design for large power plants ranging in tenths of a MW and typical unit size of 100, 150, 250, 500 and 1000 kW.

For a better understanding of the needs, constraints and possibilities of topologies and configurations for the PV-inverters, it is very helpful to use an approach similar to the one proposed in (Blaabjerg, et al. 2004; Kjaer et al., 2005). When all additional features like communication, monitoring, and safety functions are ignored, and we focus on the power electronic functions of a PV-inverter, then five basic functions can be identified for all PV-inverters: 1) *MPPT for the DC-input*: The inverter controls the DC voltage in order to operate the PV-modules at their maximum power point. The MPP varies with the insolation, the module temperature and the shading conditions. Therefore, sophisticated tracking algorithms are used. For good efficiency of the MPPT, it is important that not only the mean values of voltage and current of the module are tracked to the MPP, but also the behavior at higher frequencies has to be considered (Esram and Chapman, 2007; Azevedo et al., 2009). If the power electronic topology of the inverter introduces voltage ripples at the PV-terminals, that ripples have to be kept small, to avoid the instability of the operating point of the PV generator. Most state of the art string-inverters use a one-stage topology, in which the DC-link is directly connected to the PV-input. Controlling

the grid current (and thus the power delivered to the grid) the DC-link voltage can be influenced. But also topologies with a separate DC-DC stage for MPPT can be found (Blaabjerg et al. 2004; Salas et al. 2006). 2) *Change of the voltage amplitude*: If the PV-inverter uses a voltage sourced inverter (VSI) as a grid interface, this inverter has a buck-characteristic, meaning that its output voltage is always smaller than the input voltage. If the PV-system delivers a voltage that is smaller than the peak value of the grid voltage, a voltage boost is needed. This can be done with use of a transformer or by a DC-DC converter. 3) *Grid interface*: This is the main function block of the inverter. Most common is the use of a VSI. It can be built as a standard full-bridge for inverters with a transformer at the AC-side. 4) *Power decoupling between DC- and AC-side*: The power fluctuations between DC- and AC-side of the inverter (switching frequency and double the grid frequency for single-phase inverters) have to be decoupled by the energy storage. Most common are electrolytic capacitors forming a DC-link.

Because the minimization of the DC-link-capacity seems to be essential to achieve higher inverter lifetimes (film-capacitors could be used) a trend to 3-phase-inverters can be expected even for smaller power levels within the 1 to 5 kW ranges. 5) *Galvanic isolation between input and output*: Can be achieved by the use of transformers, operating at the grid-frequency. This may have severe drawbacks like high weight, high cost, additional losses and a non-unity power factor, especially under low load conditions. New inverter developments use high-frequency transformers. A third solution is to leave out the transformer and the isolation between input and output of the inverters. The resulting transformerless inverters have very high efficiencies, a low weight and have lower costs (Kerekes et al., 2007; Iov et al., 2010). However, the transformerless configurations require complex solutions, resulting typically in novel topologies in order to keep the leakage

and DC currents injection under control in order to comply with the safety issues.

Inverter interfacing PV module(s) with the grid involves two major tasks (Teodorescu et al., 2006; Iov et al., 2010). One is to ensure that the PV module(s) is operated at the MPP. The other is to inject a sinusoidal current into the grid. Since the inverter is connected to the grid, the standards given by the utility companies, as well as the national and the international ones must be obeyed. These standards deal with issues like power quality, detection of islanding operation, grounding, etc. This is also reflected in the chosen inverter topologies, which have changed from large thyristor-equipped grid-connected inverters to smaller IGBT- or MOSFET-equipped ones. The inverters must also be able to detect an islanding situation, and take appropriate measures in order to protect persons and equipment (LaRocca, 1992). Islanding is the continued operation of the inverter when the grid has been removed on purpose, by accident, or by damage. In other words, the grid has been removed from the inverter, which then only supplies local loads. The available detection schemes are divided into active and passive methods. The passive methods do not have any influence on the power quality, since they just monitor grid parameters. The active schemes introduce a disturbance into the grid and monitor the effect. This may affect the power quality, and problems with multiple inverters in parallel with the grid are also known to exist (IEEE Std. 929-2000, IEEE Std. 1547, 2003).

To achieve a higher power, voltage or current level for a PV system, several the PV-modules are connected in combinations of series and parallel configurations. Very common is a series connection of modules (the cells inside the modules are connected in series, too), which is called a string. The voltage of such a PV string can be between 150 V and 1000 V for grid connected PV-systems. These DC voltages are higher than the peak voltage of the grid (325 V DC for 230V AC-grids), so the inverter does not need to step-up the voltage

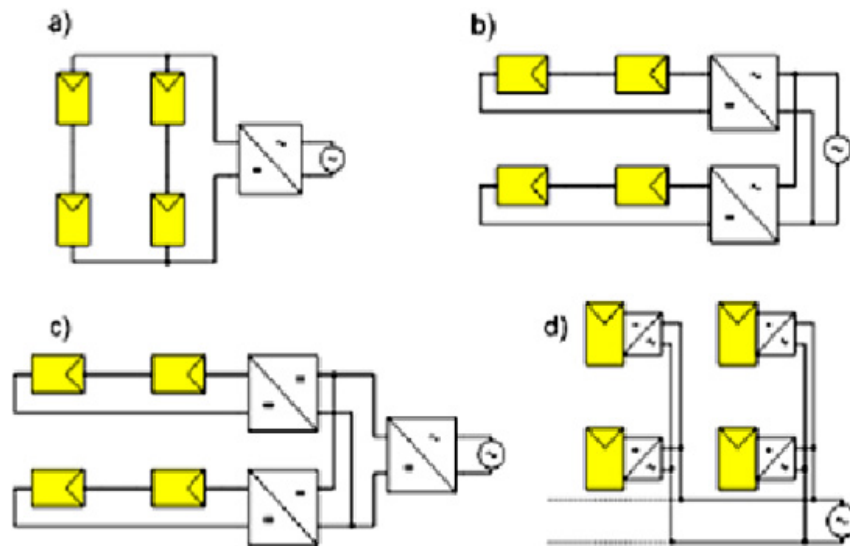
by using a DC-DC converter or a transformer. In this case often single-stage full-bridge inverters are used, which can have a high efficiency. The peak current which can be delivered by one string is determined by the size of the solar cells used in the modules. Several strings can be connected in parallel (Figure 6a) to achieve higher power. The resulting large PV system is connected to the input of a central inverter. The central inverter configuration has disadvantages especially for smaller rooftop applications, like mismatching losses between the modules or strings and missing individual MPPT for each string (Chen and Smedley, 2004, Messenger and Venter, 2010). This leads to relatively high forfeits in the energy gain from the system, when shading or different orientation of modules occurs. On the other hand, this configuration has advantages like high inverter efficiency because of the higher power level in comparison to string inverters, simplicity and low cost. Therefore, central inverters are still the first choice for medium- and large scale PV applications, where shading or different orientation of modules is avoided already at the planning stage and therefore plays no role (Solar Parks, large rooftop applications). Central inverters were mainly built with three-phase full-bridges (using IGBTs) and low-frequency transformers.

When the focus is on smaller applications, the drawbacks of central inverters become important. In many applications, the PV modules cannot be installed with the same orientation and are subject to different shading conditions during the day. For such applications the string inverter, shown in Figure 6b is the choice. Smaller inverters for each string are used here. In this case, each string has its own MPPT, which means that all strings are completely independent from each other. With this approach, it is easy to build PV-systems even under constraints like different orientation of parts of the roof, difficult shading conditions or even various types or number of PV-modules. The modules of each string should be matched and operated under the same conditions, because to

the series connection within the string. A major disadvantage of the string-inverters in comparison to the central inverters is the higher price per kW because of the rather low power level (1 to 5 kW) per unit. String inverters were built as single-phase inverters due to the low power level. A very common classic topology is the full-bridge with a low frequency transformer on the AC-side for galvanic isolation. Newer developments are often built as transformer-less inverters using special topologies, which are explained later in this chapter.

A variation of the string-inverter is the multi string-inverter shown in Figure 6c. It is a string-inverter with two (or three) inputs, providing an independent MPPT. It has the advantage that the inverter can reach a higher power level than a string inverter without having to sacrifice the advantages of the string technology. A major disadvantage is that the multi string-inverter always needs two power conversion stages to allow individual tracking at the inputs. This two-stage design leads to a smaller peak efficiency compared to a single-string inverter. On the other hand multi-string inverters have often a very wide input voltage range (due to the additional DC-DC stage), giving a larger flexibility in the PV system design. This is why the multi-string-inverters have a good acceptance. Even if the string- and multi-string inverters give more freedom in the PV system design, the modules of one string still have to be matched and should be installed in the same orientation to achieve a high-energy harvest. If the individual MPPT is extended to the level of one PV module alone, a logical solution on the inverter side is the module inverter shown in Figure 6d. These inverters are attached to only one PV-module. Because of the low power level, the devices can be small and be integrated into the housing or frame of the PV-module. The result is often called AC-module that can simply be connected to the grid. It is a big advantage that no DC-wiring is needed, because then all wiring of the PV generator can be done with normal installation material. The risk of

Figure 6. Configurations for PV systems



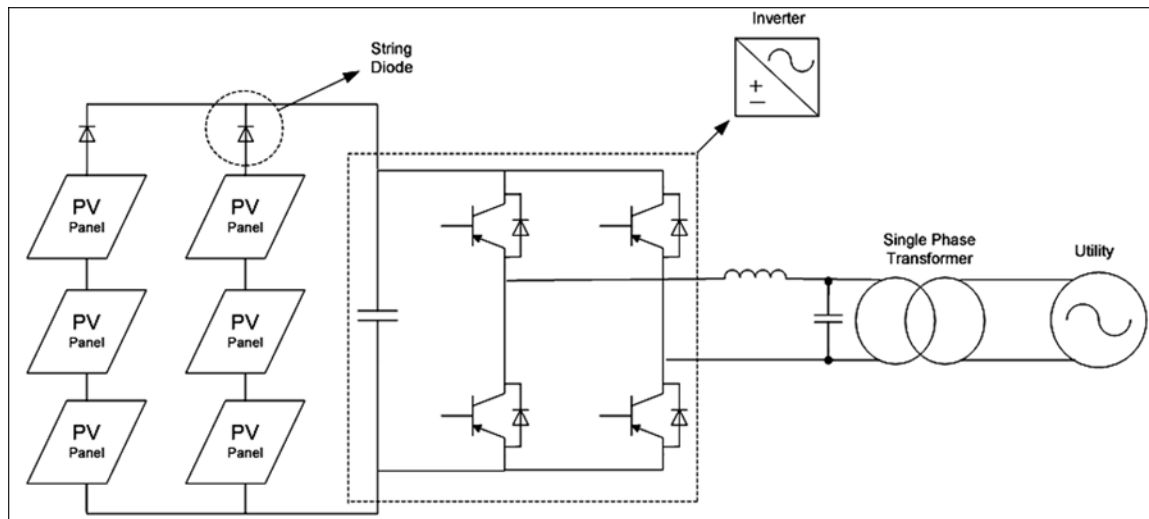
electric arcing and fire within the DC-wiring is also minimized. In spite of these advantages the module integrated inverter has still a low acceptance. This is due to several disadvantages: The low power level per unit leads to a low efficiency and high costs, which in most applications cannot be compensated by the better MPPT for each module. In addition, the packaging of PV-module and inverter to one device leads to the need for equal lifetimes of module and inverter. Current inverter technology does not reach the lifetime of PV-modules (20 years and more) therefore the bundling of inverter and module often leads to a failure of a valuable PV-module (Kalogirou, 2009, Messenger and Ventre, 2010). When the lifetime problem is solved, module integrated inverters could get very interesting because of their straightforwardness in use and installation. If they enter mass production, even the higher price due to the small power per device could be compensated. The power electronics topologies for the PV systems can also be categorized based on the number of power processing stages, the location of power decoupling capacitors, utilization transformers, and the types of grid interfaces (Carrasco et al., 2006; Boswell, 2011). The basic

classification based on the number of inverter output phases is presented next.

Single-Phase Single-Stage, Single-Phase Multiple-Stage Inverters

The most fundamental topology for a PV inverter is a single-phase, self-commutated PV system as shown in Figure 7. The DC output of the PV array is connected across a filter capacitor, used to limit the harmonic currents in the PV array. The output of the capacitor connects to a full-bridge converter and the output of the converter is connected to an inductor, limiting the high frequency harmonics injected into the AC system. A synthesized AC output voltage is produced by controlling the switches. To enable operation at or near unity power factor, the switches are controlled in response to the measured PV array output voltage to produce the required AC output voltage. The PV array is then connected to the utility grid through an electrical isolation transformer. There are several drawbacks of this topology, one being that all of the modules are connected to the same MPPT device (see the next section of this chapter

Figure 7. Single-phase single-stage PV power electronics. Adapted from Kramer et al., 2008.



for details). This causes severe power losses during partial shadowing.

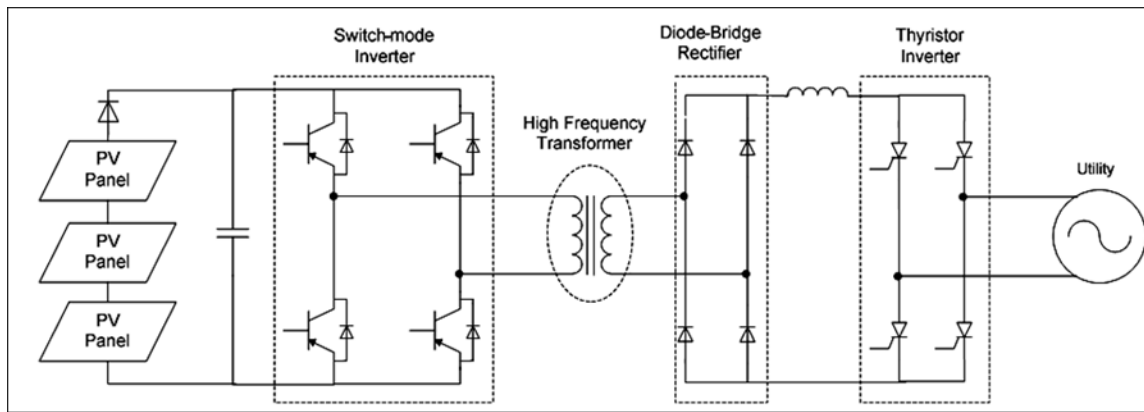
To avoid the inclusion of the low frequency transformers (a poor component mainly due to their relatively large size and low efficiency), the multiple stage (usually two-stage systems) conversion systems are widely used for PV power systems. The most common two-stage topologies consist of a DC-AC grid-connected voltage source pulse width modulation (PWM) inverter with some kind of DC-DC converters. In general, the DC-DC converter performs the maximum power point tracking (MPPT) and, perhaps, voltage amplification (Kjaer et al., 2005). The DC-AC full-bridge inverter controls the grid current. A simple design for a multiple stage PV inverter is shown in Figure 8, which utilizes a high frequency transformer for a single-phase connection to the grid (Mohan et al. 2003). The DC voltage input is inverted to produce a high frequency AC across the primary of the high frequency transformer. The transformer secondary voltage is rectified and the resulting DC output is interfaced with the line voltage through a thyristor inverter. Since the line-current is required to be sinusoidal and in phase with the line-voltage, the line-voltage

waveform is measured to establish the reference waveform for the sinusoidal line current whose amplitude is determined by a peak power-tracking controller. Several topologies exist for single-phase, dual-stage grid connected inverters as can be found in Blaabjerg et al., (2004) and Kjaer et al., (2005) or elsewhere in the literature.

Three-Phase Inverters

For systems larger than 10kW, three-phase inverters are most often used. All the configurations described for single-phase utility connection can be used for the three phase. Again, the isolation from the grid can be done either by using a line-frequency transformer or a high-frequency transformer. In the later case, an additional converter is required for converting DC from PV into high frequency AC. Figure 9 shows a typical topology for a three-phase PV inverter utilizing a line-frequency three-phase transformer. The DC output of the PV array is connected across a filter capacitor. Each phase output of the converters is connected to an LC network to limit the high-frequency harmonics injected into the AC system. A synthesized AC output voltage is produced by

Figure 8. Power electronics of single-phase multiple-stage PV systems. Adapted from Kramer et al., 2008.



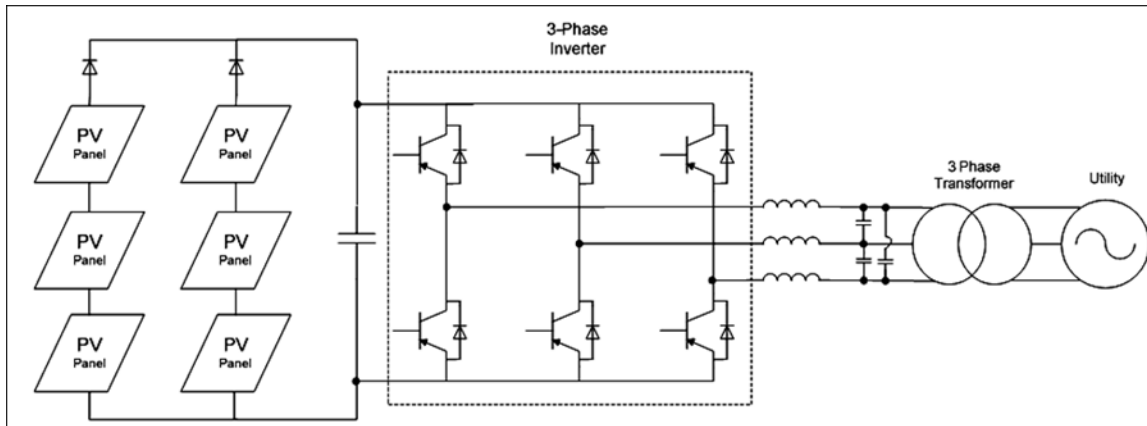
appropriately controlling the switches. A three-phase transformer is then used to connect the PV system to the grid.

Different configurations without transformers can be used for the PV system; however, such topologies are more for the European countries and Japan where system grounding is not mandatory for the PV inverters. The PV modules be system grounded and monitored for ground faults when the maximum output voltage of the PV modules reaches a certain level (e.g., 50 V) (Kjaer et al., 2005; Kerekes et al., 2007). Only a few transformer-free, high-input voltage topologies that can be grounded both at the input and at the output are yet known. Modern inverters tend to use a high-frequency transformer for galvanic isolation. This technology results in entirely new designs, such as the printed circuit board (PCB) integrated magnetic components (Kjaer et al., 2005). One such design is shown in Figure 9, where the transformers are embedded in high-frequency DC-DC converters. Such a topology is also very useful for multi-string configurations, where each of the strings can be connected to a common DC bus and then converted to grid compatible AC by using a single DC-AC inverter.

Island Inverters

While the low voltage grid supplies sinusoidal electric energy of 120V/60 Hz (or 230 V/50- Hz in Europe), island inverters are subdivided into three main groups according to their voltage wave-forms: rectangular, trapezoidal, and sine inverters. For low power range, e.g. for the local supply of individual AC loads within a DC grid, very often rectangular or trapezoidal inverters are used, due their very simple structure and operation. For larger systems (more than 1 kW), sine-wave inverters are most commonly employed. In recent years, there is an increased tendency to use sine-wave inverters for small-scale applications. The rectangular and trapezoidal inverters consist of a four-switch bridge controlled by an appropriate circuitry. The main disadvantage of the rectangular inverter is that the output voltage is direct proportional to the fluctuations of the DC source voltage. In the case of the trapezoidal inverter, the output voltage contains a blanking interval, its width being adjusted by the controlling circuit in such way that even for different input voltages an almost constant actual output voltage can be achieved. During the operation of such inverters it is needed to check whether the intended consumer, generally designed for sine wave voltages can perform reliable under the given voltage conditions. The

Figure 9. Three-phase PV topology with line-frequency transformer. Adapted from Kramer et al., 2008.



output voltage of the sine inverter is identical to that of the utility supply, so all consumers can be provided with power useable without any problems. They are built in a great variety of topologies. Unlike rectangular inverters the input voltage is “chopped” at much higher frequencies (some 10 kHz to a few 100 kHz). A downstream filter is included to suppress all high-frequency components of the signal and to generate the desired sinusoidal waveform voltage, while the downstream transformer adjusts the voltage to the required voltage. This system component may be omitted in case of sufficiently high input voltage, reducing the cost and increasing the efficiency. For stand-alone or isolated local grids, such high input voltages are currently only applied for large power plants, mainly due to the requirements of the battery and/or other energy storage systems. However, due to the risk of the individualization of different solar cells, the batteries are difficult to operate at high voltage levels than at low voltages. For power plant installed capacity less than 10 kW input voltages usually vary between 48V and 60 V. To avoid the above shortcomings, the usually topology includes a DC-DC converter between the battery and the inverter supplying the appropriate voltage level. This concept allows the transformerless inverter design for any type of PV system. A major disadvantage of all trans-

formerless topologies is the fact that they have no conduction separation and therefore additional safety features must be integrated. Regardless of the application and topology, the requirements for all inverters are: a) high efficiency; b) low self consumption; c) stable operation behavior; d) entire voltage range coverage; and e) sinusoidal output voltage without DC bias. The current trend for the larger standalone hybrid systems consists of the use of the bi-directional inverters, allowing battery charging from additional generators (wind, hydropower, fuel cells, diesel generators, etc.)

Grid-Connected Inverters

To feed PV systems into the grid, inverters are required to convert DC generated power into AC power compatible with the mains. The inverters for PV grid-integrated systems are usually direct connected to the PV systems without any storage. Unlike as earlier grid-connected inverters, modern semiconductor components, in conjunction with optimized circuit topologies allow the development of special PV inverters with significantly improved properties and characteristics. For example, the system self-consumption has been significantly reduced, so the required efficiency over 90% could be reached at a nominal output power of 10%. Besides the low self-consumption,

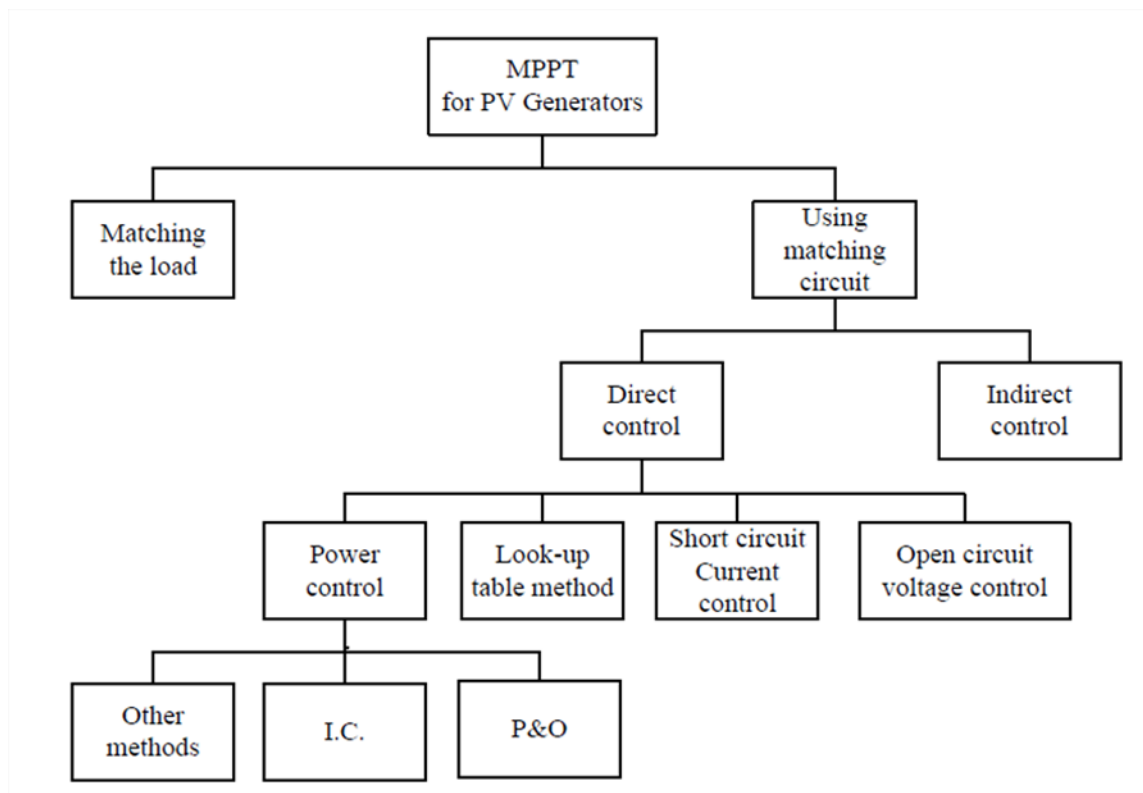
grid-connected inverters are characterized by very high efficiencies at rated power. There is a wide power range of devices and configurations on the market from 10 W up to hundreds of KW, as well as a wide range of functional principles is applied.

Grid-commuted inverters need, due to their design, a strong power grid to function. They are using thyristors as switching elements, due to their robustness and cost. Such inverters, generally grossly distort the supplied output voltage, and cause phase shifts with regard to the mains voltage. For these reasons, they require additional filter and compensation measures. Other configurations, especially, within the low power range are now used. Self-commuted inverters are based on disengage able power switch, so an external grid is not required for normal operation. A widely used principle is the pulse width modulation (PWM) offering a wide range of circuit topologies.

Grid-connected inverters must be synchronized with grid; in the case of grid failure, the inverter operation must be prevented for safety reasons. To minimize the risk of islanding while the mains is disconnected, in many countries, it is required by law to supervise the single-phase PV systems to ensure that maintenance at the grid can be performed safely.

If the input voltage is sufficiently high, the inverters can directly feed into the grid without transformer for voltage adjustment. Besides reducing the cost, weight and volume, the transformerless configurations reduce the self-consumption and improve the efficiency especially in the partial-load range. On the other hand, the devices provided with transformer may be categorized into systems equipped with a 50/60 Hz transformer and systems provided with high-frequency transformers. The later offers weight and volume advantages on the

Figure 10. Flowchart of the most used MPPT methods and algorithms



expenses of higher losses and failure probability due to more complex overall circuit layout.

MAXIMUM POWER POINT TRACKING SYSTEMS FOR PHOTOVOLTAICS

The output current of PV panels varies depending on the status of the load. Figures 12(a) and (b) are I-V and P-V characteristics of a certain PV panel, respectively. Over a wide range of current and voltage, it is essential to find a point that maximizes the output power. The point maximizing the power consequently enables users to extract maximum capable power from the PV cell. The point is called the Maximum Power Point (MPP) and finding this point is called Maximum Power Point Tracking (MPPT). Here tracking does not mean physical movement e.g., following on the sun. MPPTs play an important role in PV power systems because they maximize the power output from a PV system for a given set of conditions, and therefore maximize the array efficiency. Thus, an MPPT can minimize the overall system cost. MPPTs find and maintain operation at the maximum power point, using an MPPT algorithm. Many such algorithms have been proposed, over the years (Hohm and Ropp, 2003). MPPT algorithms are necessary because PV arrays have a non-linear voltage-current characteristic with a unique point where the power produced is maximum (Hohm and Ropp, 2003); Salas et al., 2006; Esram and Chapman, 2007). This point depends on the temperature of the panels and on the irradiance conditions. Both conditions change during the day and are different depending on the season of the year. Furthermore, irradiation can change rapidly due to changing atmospheric conditions such as clouds. It is very important to track the MPP accurately under all possible conditions so that the maximum available power is always obtained. In the past years, numerous MPPT algorithms have been published (Femia et al., 2004, 2005, 2006

and 2007). They differ in many aspects such as complexity, sensors required, cost or efficiency. However, it is pointless to use a more expensive or complicated method if with a simpler and less expensive one similar results can be obtained. This is the reason why some of the proposed techniques are not used. Measuring the efficiency of MPPT algorithms has not been standardized until the European Standard EN 50530 was published at the end of May 2010. It specifies how to test the efficiency of the MPPT methods both statically and dynamically.

Tracking the MPP of a photovoltaic array is usually an essential part of a PV system. Over the years, many MPPT methods have been developed and implemented. As such, many MPPT methods have been developed and implemented (Salas et al., 2006; Esram and Chapman, 2007; and Dolara et al., 2009). Rodriguez and Amaratunga (2007) developed a mathematical model using the mean value theorem providing the analytic solution of a point in a close neighborhood of the MPP. They proved that this point is enclosed in a ball of small radius that also contains the MPP and therefore can practically be considered as the MPP. Since the solution is analytic, no iterative schemes are necessary in this approach, and only a periodic measurement is required to adjust to changes in solar irradiance. A circuit was implemented based on this analytic solution that proved the validity of the theory and the accuracy of the solution.

However, the MPPT methods vary in complexity, sensors required, convergence speed, cost, range of effectiveness, implementation hardware, popularity, and in other respects. The names of some of these methods are hill climbing, perturb and observe (P&O), incremental conductance (InCond), fractional open-circuit voltage, fractional short-circuit current, fuzzy logic and neural network controls, ripple correlation control, current sweep, DC-link capacitor droop control, load-current or load-voltage maximization, and dP/dV or dP/dI feedback control. The detailed overview of these MPPT methods can be found

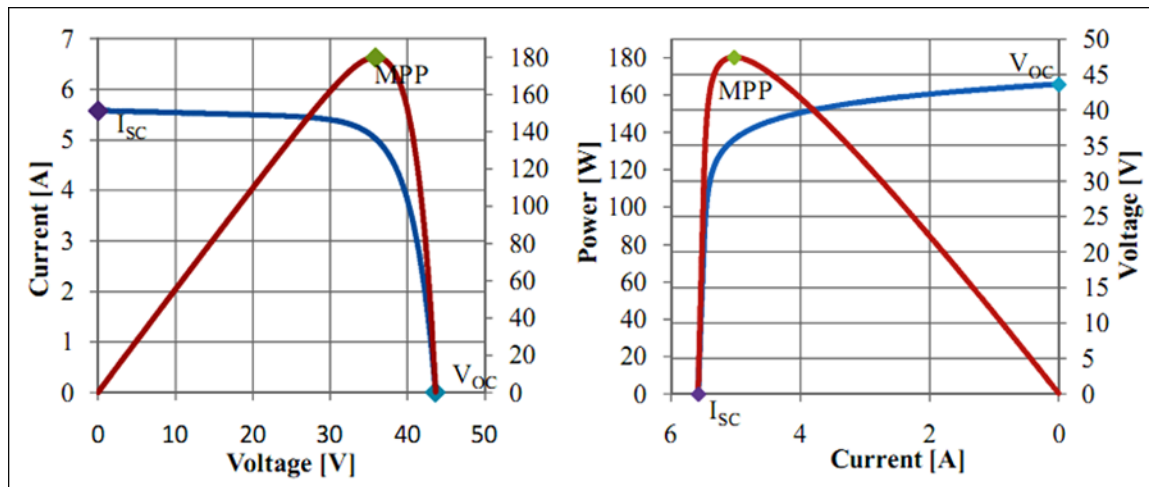
in Hohm and Ropp, (2003), Salas et al., (2006), or Esram and Chapman, (2007). They range from the almost obvious (but not necessarily ineffective) to the most creative algorithms (not necessarily most effective). In fact, so many methods have been developed that it has become difficult to adequately determine which method, newly proposed or existing, is most appropriate for a given PV system. Figure 10 shows a diagram summarizing the most common used MPPT methods and algorithms. The number of papers focusing on the MPPT methods, algorithms and implementation per year has grown considerably of the last three decades and remains strong.

A PV array under constant uniform irradiance has a current–voltage (I–V) characteristic like that shown in Figure 11. There is a unique point on the curve, called the MPP, at which the array operates with maximum efficiency and produces maximum output power. When a PV array is directly connected to a load (a so-called ‘direct-coupled’ system), the system’s operating point will be at the intersection of the I–V curve of the PV array and load line shown in Figure 11. In general, this operating point is not at the PV array’s MPP, which can be clearly seen in Figure 11. Thus, in a direct-coupled system, the PV array must usually be oversized to ensure that the load’s power requirements can be supplied. This leads to an overly expensive system. To overcome this problem, a MPPT is used to maintain the PV array’s operating point at the MPP. The MPPT does this by controlling the PV array’s voltage or current independently of those of the load. If properly controlled by an MPPT algorithm, the MPPT can locate and track the MPP of the PV array. However, the location of the MPP in the I–V plane is not known apriori. It must be located, either through model calculations or by a search algorithm. The situation is further complicated by the fact that the MPP depends in a nonlinear way on irradiance, temperature, PV cell surface characteristics, etc. (Kalogirou, 2009).

When properly applied, a maximum power point tracking control can prevent the collapse of the array voltage under excessive load demand, particularly when supplying a constant-power type of load. One of the proper approaches is to operate the system in a solar array voltage regulation mode where the array voltage is clamped to a commanding set point, which is dynamically updated by the MPPT control circuit. The control process feedback signals, such as the array current and voltage, to determine a proper direction to move the operating point. Eventually, this continuously updated set point will fluctuate around the voltage corresponding to the array peak power point. By adjusting the operating point of the array to the set point, the array power output is maximized, and the most efficient use of the solar array may be realized. For a system without MPPT, the voltage will quickly collapse to zero. This phenomenon can be understood from the I–V characteristic of a solar array. The flatness of the I–V curve on the left of the MPP implies that a small incremental increase in current demand leads to large voltage change. A system with MPPT avoids the voltage collapse by keeping the operating point near the MPP. On the I–V curve, the operating point corresponding to the MPP is around the “knee” region (see Figure 11). Therefore, unlike other power systems with stiff voltage sources, the power conversion from the PV systems with MPPT requires a more robust design due to the risks of voltage collapse under the peak load demand or severe changes in the PV array characteristics.

From the previous discussion, it can be observed that the most generalized form of power electronics topology for the PV application is the DC–DC converter with embedded high-frequency transformer, along with the DC–AC inverter as shown in Figure 12. Usually, the MPPT and voltage boost are done by the DC–DC converter. The power flow control to the utility and the sinusoidal unity power factor current-injection to the utility are produced by the DC–AC inverter controller.

Figure 11. PV panel characteristic curves

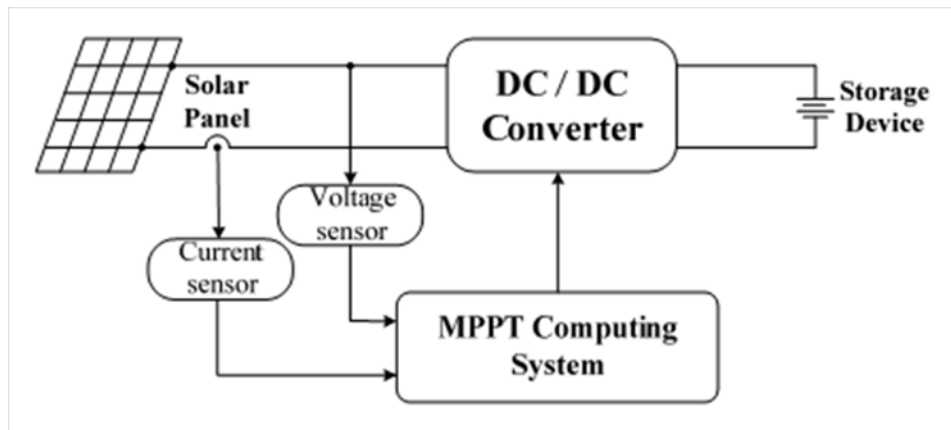


A simplified block diagram of the PV system with the power electronics and control is given in Figure 12. Usually the power electronics circuit consists of a DC-DC converter and an inverter. The inverter includes galvanic isolation between the PV system and the grid, so the PV strings can be easily system-grounded and compatible with the NEC Article 690 requirements. The current-source input stage is beneficial since it reduces the requirement for the filter capacitor in parallel with the PV strings. Furthermore, the diodes included in the rectifiers are current-commutated, involving low-reverse recovery of the diodes and low voltage stress (Kjaer et al., 2005; Iov et al., 2010). The voltage from the PV string is first converted into a high frequency AC; galvanic isolation with voltage boosting is accomplished with a high-frequency transformer. The transformer secondary voltage is then rectified using a full-bridge diode rectifier. The rectified DC is then converted into grid compatible AC and connected to the utility by a three-phase voltage-source inverter.

The MPPT is now prevalent in grid-tied PV power systems and is becoming more popular in stand-alone systems. It should not be confused with sun trackers, mechanical devices that rotate and/or tilt PV modules or arrays in the direction of

sun. MPPT is a power electronic circuit interconnecting a PV power source and a load or grid. It maximizes the power output from a PV module or array with varying operating conditions, and therefore maximizes the system efficiency. MPPT is made up with a switch-mode DC-DC converter and a controller. For grid-connected systems, a switch-mode inverter sometimes fills the role of MPPT. Otherwise, it is combined with a DC-DC converter that performs the MPPT function. In addition to MPPT, the system could also employ a sun tracker. The power-matching scheme requires the panels to have suitable output characteristics that can match with particular loads. Figure 12b shows an equivalent circuit of the solar panel connecting to an MPPT, modeled by a Thevenin's equivalent circuit, consisting of a voltage source connected in series with an output resistance around the MPP. Both the generator voltage and current are subject to the level of insolation and temperature. In addition to MPPT, the system could also employ a sun tracker. According to the data in reference (Shimazu et al., 2003), the single-axis sun tracker can collect about 40% more energy than a seasonally optimized fixed-axis collector can in summer in a dry climate such as Albuquerque, New Mexico. In winter, however,

Figure 12. Typical block diagram of a solar system



it can gain only 20% more energy. In a climate with more water vapor in the atmosphere, the effect of sun tracker is smaller because a larger fraction of solar irradiation is diffuse. It collects 30% more energy in summer, but the gain is less than 10% in winter. The two-axis tracker is only a few percent better than the single-axis version. Sun tracking enables the system to meet energy demand with smaller PV modules, but it increases the cost and complexity of system. Since it is made of moving parts, there is also a higher chance of failure (Kalogirou, 2009).

The use of sun trackers schemes in conjunction with the MPPT control strategies has been demonstrated to be very useful in order to get higher efficiency in photovoltaic plants (Alboteanu et al. 2006, Cañada et al., 2007). The basis of sun tracker equipment is to hold the PV array in the best position regarding the sun location during the sunny time. This can be done by means of single axis (azimuth) or dual axes (azimuth and elevation) systems. The system presented in this work belongs to the last category. The sun tracker is usually composed by a mechanical mainframe that supports the PV array and its electronic control system that allows its movement in two axes. Wai et al., (2006) developed a grid-connected PV generation system with an adaptive step-perturbation (ASP) method and an active sun-tracking

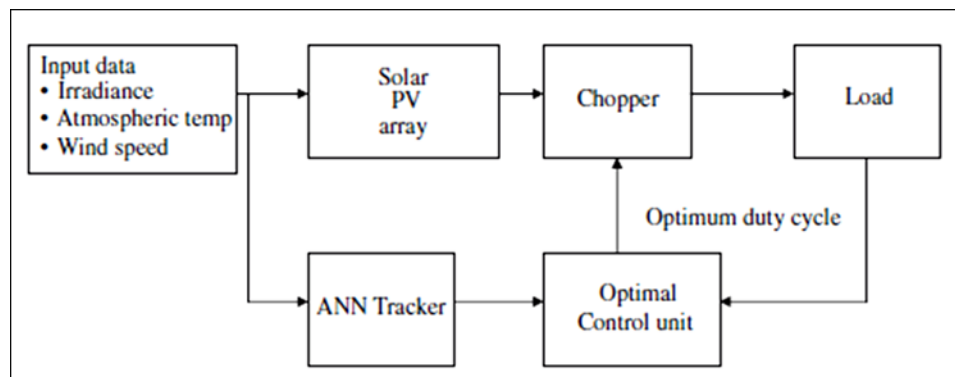
scheme. The effectiveness of the ASP method, and the active sun tracker for a grid-connected PV generation system was verified by realistic experimentations. According to the experimental results, the ASP method provides faster tracking response and overcomes the oscillation problem in the conventional P&O method for reducing extra power losses. Moreover, the implementation of the active sun-tracking scheme because of the open-circuit voltage of PV modules is to improve the generation efficiency of the fixed-installation PV array, and to save the cost of the conventional sun tracker with light sensors. In order to increase the efficiency and reduce the cost of a PV system, Jaen et al., (2009) proposed to combine a MPPT with a Sun Tracker (see Figure 13). In their work the use of a sun tracker system is proposed as an additional improvement applied to a photovoltaic installation that works under a MPPT control technique. Proposed system consists of PV module, boost converter, P&O controller and sun tracker equipment. Experimental results show good performance. Comparing data in terms of energy, the PV array performances are rather improved by the use of the sun tracker equipment. Other implementations of the combined MPPT and sun tracking involves the intelligent techniques will be discussed later.

The MPPT methods vary in complexity, sensors required, convergence speed, cost, range of effectiveness, implementation hardware, popularity, and in other respects. Among these techniques, P&O and incremental conductance algorithms are the most common. Most of the MPPT methods yield a local maximum and some, like the fractional open circuit voltage or short circuit current, give an approximated MPP, not the exact one. In normal conditions, the V-P curve has only one maximum, so it is not a problem to find it. However, if the PV array is partially shaded, there are multiple maxima in these curves. In order to relieve this problem, some new algorithms have been implemented as in (Bellini et al., 2010, Nguyen and Low, 2010, Petreus et al., 2010). In the next section, the most popular MPPT techniques are discussed. The total number of MPPT papers from our bibliography survey per year since the earliest MPPT papers we found increased dramatically and remain strong. In the next subsections of this chapter, we introduce and discuss the different MPPT techniques, methods and algorithms, as well as the use of these techniques and algorithms in the practical applications.

Hill-Climbing/Perturb and Observe MPPT Algorithms

Most MPPT algorithms and techniques are based on the hill-climbing method and the MPP is found by changing the reference voltage of the PV, so the extracted power is always the highest one for the present irradiation and temperature. Both P&O and InCond algorithms are based on the “hill-climbing” principle, which consists of moving the operation point of the PV array in the direction in which power increases (Femia et al., 2005, 2006 and 2007; Nguyen and Low, 2010). Hill-climbing techniques are among the most popular MPPT methods due to the ease of implementation and good performance when the irradiation is constant (Sera et al., 2006a, and 2006b). The advantages of both methods are the simplicity and low computational power required. The shortcomings are also well-known: oscillations around the MPP and they can get lost and track the MPP in the wrong direction during rapidly changing atmospheric conditions (Husein et al., 1995; Sera et al. 2006a and 2006b; Nguyen and Low, 2010). The P&O algorithm is also called “hill-climbing”, but both names refer to the same algorithm depending on how it is implemented. Hill-climbing involves a perturbation on the duty cycle of the power converter and P&O a perturbation in the operating

Figure 13. Block diagram of a photovoltaic system including MPPT control and sun tracker equipment (Adapted from Jaen et al., 2009)



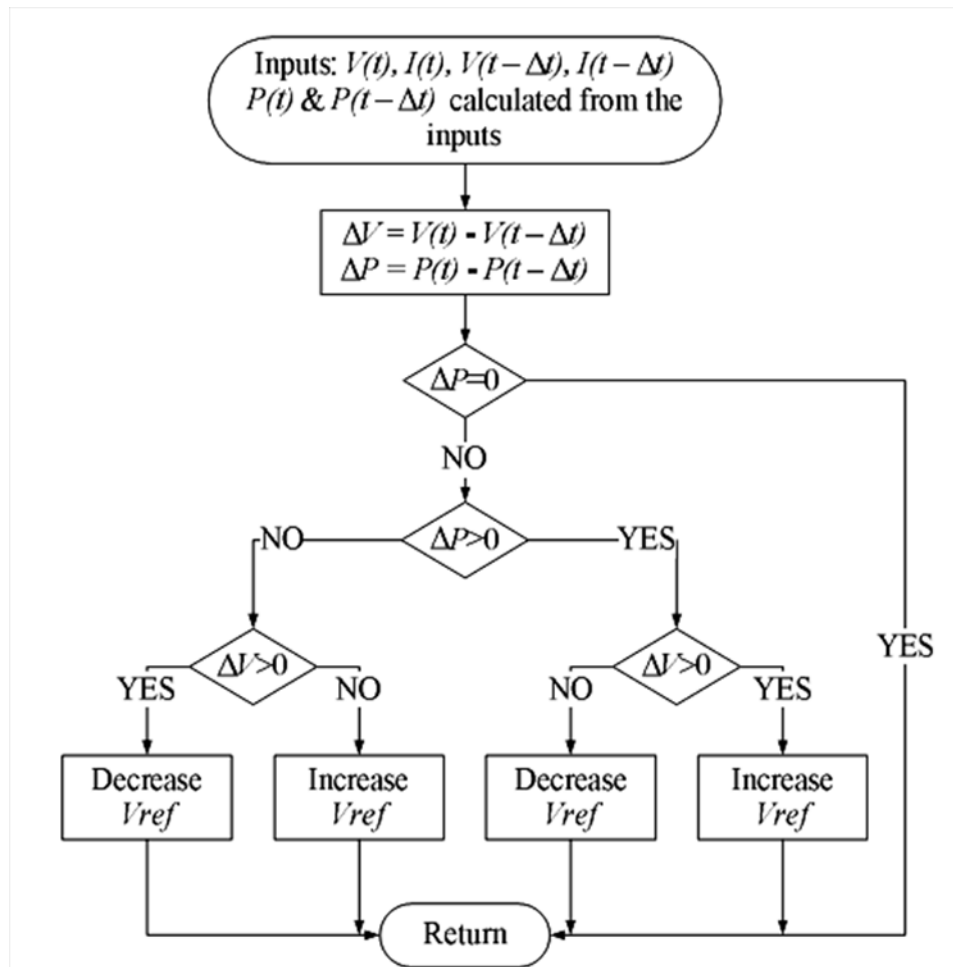
voltage of the DC link between the PV array and the power converter (Salas et al., 2006, Esum and Chapman, 2007, Azevedo et al., 2009). In the case of the hill-climbing, perturbing the duty cycle of the power converter implies modifying the voltage of the DC link between the PV array and the power converter, so both names are basically referring to the same technique. The sign of the last perturbation and the sign of the last increment in the power are used to decide what the next perturbation should be. The flowchart of this algorithm is shown in Figure 14. As can be seen in Figure 14, on the left of the MPP incrementing the voltage increases the power whereas on the right decrementing the voltage increases the power.

The P&O MPPT algorithm is based on the following criterion: if the operating voltage of the PV array is perturbed in a given direction and if the power drawn from the PV array increases, this means that the operating point has moved toward the MPP and, therefore, the operating voltage must be further perturbed in the same direction. Otherwise, if the power drawn from the PV array decreases, the operating point has moved away from the MPP and, therefore, the direction of the operating voltage perturbation must be reversed. If there is an increment in the power, the perturbation should be kept in the same direction and if the power decreases, then the next perturbation should be in the opposite direction (Femia et al., 2005; Esum and Chapman, 2007). The process is repeated until the MPP is reached, as shown in Figure 15. A drawback of P&O MPPT technique is that, at steady state, the operating point oscillates around the MPP giving rise to the waste of some amount of available energy. Several improvements of the P&O algorithm have been proposed in order to reduce the number of oscillations around the MPP in steady state, but they slow down the speed of response of the algorithm to changing atmospheric conditions and lower the algorithm efficiency during cloudy days (Hussein et al., 1995; Rooji et al., 2000). Then the operating point oscillates around the MPP. This

problem is common also to the InCond method, as was mentioned earlier. Both P&O and InCond methods can be confused during those time intervals characterized by changing atmospheric conditions, because, during such time intervals, the operating point can move away from the MPP instead of keeping close to it. This drawback is shown in Figure 16 (Femia et al., 2005 and 2006) where the P&O MPPT operating point path for an irradiance variation from 200 W/m^2 to 800 W/m^2 is reported. The example shown in Figure 16 presents two different behaviors in the plane output power vs. voltage: Figure 16a) shows the operating point path in presence of slowly changing atmospheric conditions, while Figure 16b), instead, shows the failure of MPPT control to follow the MPP when a rapid change in atmospheric conditions occurs.

In the case of most single-stage grid connected PV systems, the control is acting on the grid side current only, which means that the MPPT is directly adjusting the amplitude of the grid current. Hill-climbing involves a perturbation in the duty ratio of the power converter and P&O a perturbation in the operating voltage of the PV array. In the case of a PV array connected to a power converter, perturbing the duty ratio of power converter perturbs the PV array current and consequently perturbs the PV array voltage. Hill-climbing and P&O methods are different ways to envision the same fundamental method. From Figure 15, it can be seen that incrementing (decrementing) the voltage increases (decreases) the power when operating on the left of the MPP and decreases (increases) the power when on the right of the MPP. Therefore, if there is an increase in power, the subsequent perturbation should be kept the same to reach the MPP and if there is a decrease in power, the perturbation should be reversed. D'Souza et al. (2005) shown that the algorithm also works when instantaneous (instead of average) PV array voltage and current are used, as long as sampling occurs only once in each switching cycle.

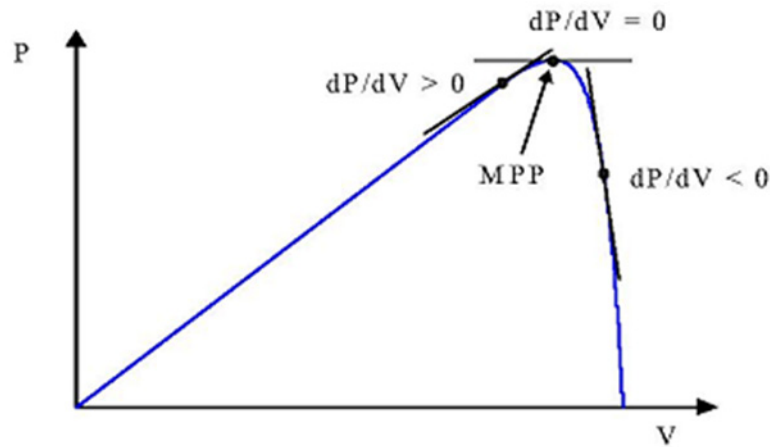
Figure 14. The flowchart of the P&O algorithm



The process is repeated periodically until the MPP is reached. The system then oscillates about the MPP. The oscillation can be minimized by reducing the perturbation step size. However, a smaller perturbation size slows down the MPPT. Solution to this conflicting situation is to have a variable perturbation size that gets smaller towards the MPP (Al-Amoudi and Zhang, 1998; Hua and Lin, 2001; Xiao and Dunford, 2004; Femia et al., 2005, 2006 and 2008; Kim et al., 2006). Hua and Lin, (2001) proposed a three-loop operation control for the photovoltaic power system with parallel operation. Instantaneous power sharing control is used in this study to achieve the current

distribution and ensure a fast dynamic response, an adjustable load sharing capability and eliminate the circulation current. The system controller is based on a DSP algorithm in order to simplify the circuit and it is easy to modify the system. A modified method of tracking the PV MPP's and forcing the system to operate close to these points is proposed. The results of the computer simulation and experiments show that the single module inverter has good voltage regulation and quick transient responses. In multi-module inverter parallel operation, in order to achieve power sharing, the instantaneous power sharing method is usually adopted to ensure that the system has the

Figure 15. Sign of the dP/dV at different positions on the power characteristic

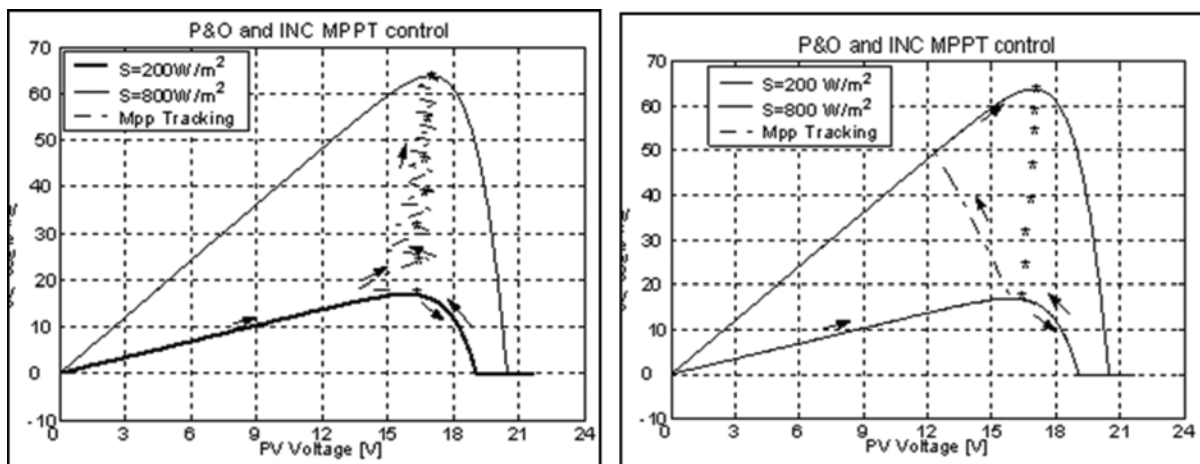


ability to provide different current according to the system rating or the command. The analysis of the computer simulation and the waveforms of the circuit experiments indicate that the designed controller features good performance and fast transient response. Moreover, in order to reach the goal of minimizing the system volume and

increasing expanding flexibility, the system is operated by digital controller.

D'Souza et al., (2005) proposed a fuzzy logic (FL) based P&O MPPT with peak current control with variable variation of the reference current for improved transient as well as steady state performance. The proposed FL-based P&O MPPT

Figure 16. P&O MPPT operating point path. The * represents MPP for different levels of the irradiance: a) slow change in atmospheric conditions, b) rapid change in atmospheric conditions Adapted from Femia et al. 2005.



a)

b)

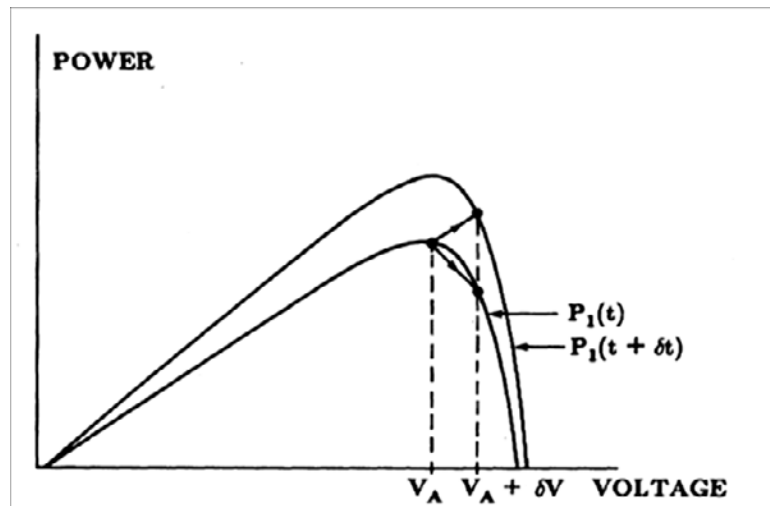
algorithm with peak current control and sampling of instantaneous, not averaged, values. It outputs a reference current that is adjusted with variable variations as a function of the variations of the instantaneous values of the PV array current and power. Simulation results show a 15% gain in the transient response and decrease of the power loss in the steady state. In this way very fast transient responses are achieved, while reducing the oscillations around the MPP in the steady state. The remaining power loss in the steady state is due only to the current ripple. Jain and Agarwal, (2004) proposed a two-stage algorithm offering first stage faster tracking and finer tracking in the second stage. The new algorithm was capable of rapid tracking of the MPP in PV systems by using a variable iteration step-size and a non-linear estimate of the initial value of the MPP reference. The algorithm brings the operating point very close to the actual MPP with a few iterations. Hill-climbing or incremental conductance methods with finer steps can, then, be used to track the exact MPP. The proposed algorithm has the advantage of very fast convergence and accurate tracking of MPP, and it is quite efficient during the transient tracking phase, as compared to conventional methods and is especially suitable for fast changing environmental conditions. This algorithm has been verified on a PV system modeled in MATLAB–Simulink. The algorithm significantly improves the efficiency during the tracking phase as compared to a conventional algorithm. It is especially suitable for fast changing environmental conditions. Tafticht and Agbossou (2004), bypass the first stage by using a nonlinear equation to estimate an initial operating point close to the MPP. Besides, that all of these P&O schemes with fixed variation for the reference current and the intelligent MPPT algorithm were able to identify the global MPP in a partially shaded PV module. However, the performance of the intelligent MPPT algorithm was better.

Hill-climbing and P&O methods can fail under rapidly changing atmospheric conditions

as illustrated in Figure 17. Starting from an operating point A, if atmospheric conditions stay approximately constant, a perturbation ΔV in the PV system voltage will bring the operating point to a point and the perturbation will be reversed due to a decrease in power. However, if the irradiance increases and shifts the power curve from P_1 to P_2 within one sampling period, the operating point will move from A to C. This represents an increase in power and the perturbation is kept the same. Consequently, the operating point diverges from the MPP and is continuing to diverge if the irradiance steadily increases. To ensure that the MPP is tracked even under sudden changes in irradiance, Hsiao and Chen, (2002) uses a three-point weight comparison P&O method that compares the actual power point to two preceding ones before a decision is made about the perturbation sign. In this way avoids the oscillation problem of the perturbation and observation MPPT algorithm. Xiao and Dunford, (2004) proposed an improved algorithm toggling between the traditional hill-climbing algorithm and a modified adaptive hill-climbing mechanism to prevent deviation from the MPP. The simulation and experimental results show that the proposed MPPT control can avoid tracking deviation and result in improved performance in both dynamic response and steady state.

As we mentioned before, the major drawbacks of the MPPT P&O algorithms are the oscillations. The operating point oscillates around the MPP at steady state giving rise to the waste of some amount of available energy. The P&O algorithm can be confused during those time intervals characterized by rapidly changing atmospheric conditions. In order to handle the above stated drawbacks of P&O, Femia et al., (2005) and (2006) proposed a method based on the optimization of the sampling rate. The idea underlying the proposed optimization approach lies in the customization of the P&O MPPT parameters to the dynamic behavior of the whole system composed by the specific converter and PV array adopted. A theoretical analysis allowing the optimal choice of such parameters

Figure 17. PV array power vs. voltage at two insolation levels (adapted from Wasynczuk, 1983)



was also carried out. The results obtained by means of such approach have shown that in the design of efficient MPPT regulators, the easiness and flexibility of P&O MPPT control technique can be exploited by optimizing it according to the specific system's dynamic characteristics. D'Souza et al., (2005) simply uses a high sampling rate to avoid these drawbacks. In this way, very fast transient responses were achieved, while reducing the oscillations around the MPP in the steady state.

MPPT algorithms usually require two sensors to measure the PV array voltage and current from which power is computed. However, depending on the power converter topology, only a voltage sensor might be needed as in proposed by Veerachary et al., (2001) and Wolfs and Tang, (2005). Kasa et al., (2005) estimated the PV array current from the array voltage, eliminating the need for a current sensor. A sensorless current flyback inverter has been proposed in this work to be applied to a PV system guided by MPPT operation. This sensorless method can contribute to the space saving and cost reduction of the PV power conditioner. The experimental data show that the sensorless current flyback inverter can be applied to MPPT for the PV small power system

with good performance. DSP or microcomputer control is more suitable for hill-climbing and P&O even though discrete analog and digital circuitry can be used, as proposed by Kim et al., (1996). Lim and Hamill, (2000) proposed an MPPT algorithm derived from the nonlinear dynamics. Although the control circuit is extremely simple and robust, its dynamics are complex. The MPP becomes inherently the global attractor of the system, thus ensuring optimum operation under transient and steady state conditions. Experimental results confirm excellent tracking effectiveness and rapid dynamic response. Although its dynamics are complex and are still under investigation, the circuit appeals, because it is far simpler than the most MPPTs, is robust and performs well. It is also worth to mention that the issue of P&O MPPT has been addressed in different ways and several implementations are presented in the literature of the last decade (Salas et al., 2006; Azevedo et al., 2009; and Boxwell, 2011). For low-cost implementations, the P&O MPPT algorithm is the most commonly used method due to its ease of implementation (Salas et al., 2006, Esum and Chapman, 2007, and Azevedo et al., 2009).

Constant Voltage Method

The constant voltage (CV) algorithm is the simplest PV system MPPT control method. In this method the operating point of the PV array is kept near the MPP by regulating the array voltage to match a fixed reference voltage equal to the V_{MPP} of the PV panel (Franda and Leva, 2008, Dolara et al. 2009). The CV method assumes that individual insulation and temperature variations on the array are insignificant, and that the constant reference voltage is an adequate approximation of the true maximum power point. Therefore, the operating point is never exactly at the MPP and different data have to be adopted for different locations and geographical areas. The CV method does not require any input. However, the measurement of the PV voltage V_{PV} is necessary in order to set up the duty-cycle of the DC-DC converter, as shown in the flowchart of Figure 18. It is important to observe that when the PV panel is in low insulation conditions, the CV technique is more effective than either the P&O method or the IncCond method (analyzed below) as analyzed by Yu et al., (2004) or Dolara et al., (2009). Due to these characteristics, the CV method is often combined with other MPPT techniques. Using this approach, Yu et al., (2004) developed a novel two-mode MPPT control algorithm.

Incremental Conductance Algorithms

The incremental conductance (IncCond) algorithm is based on the fact that the slope of the curve power vs. voltage (current) of the PV module is zero at the MPP, positive (negative) on the left of it and negative (positive) on the right, as can be seen in Figure 12:

- $\Delta V/\Delta P = 0$ ($\Delta I/\Delta P = 0$) at the MPP
- $\Delta V/\Delta P > 0$ ($\Delta I/\Delta P < 0$) on the left
- $\Delta V/\Delta P < 0$ ($\Delta I/\Delta P > 0$) on the right

By comparing the increment of the power vs. the increment of the voltage (current) between two consecutive samples, the change in the MPP voltage can be determined. The slope and power derivative are given by the equation:

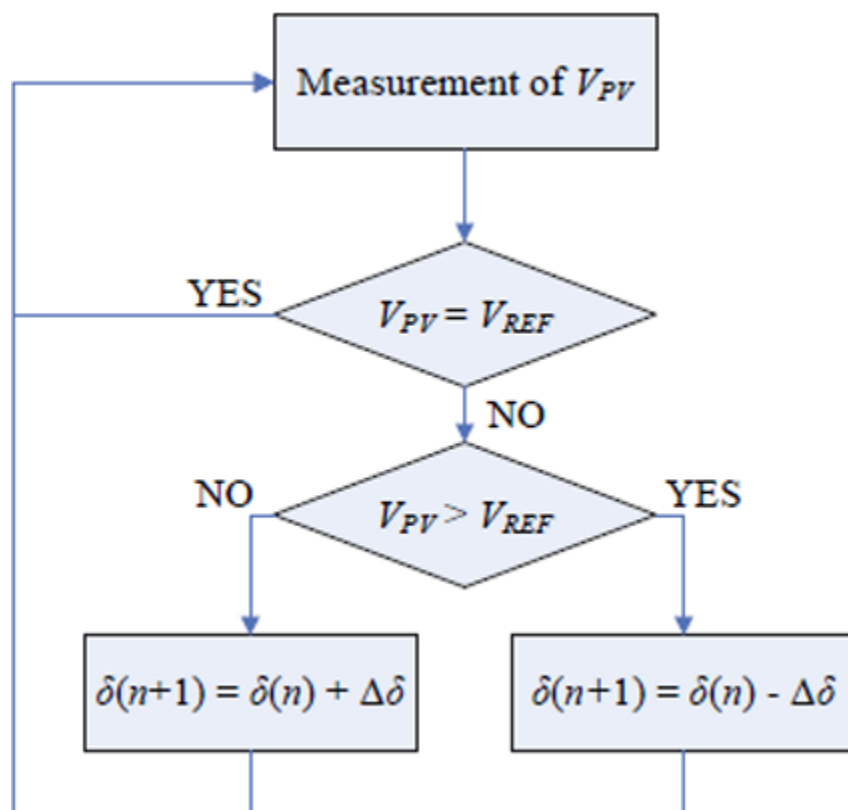
$$\frac{dP}{dV} = I + V \frac{dI}{dV} \cong I + V \frac{\Delta I}{\Delta V} \quad (2)$$

The maximum condition implies that $dP/dV = 0$, and so:

$$I + V \frac{\Delta I}{\Delta V} = 0 \quad (3)$$

The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$) as shown in the flowchart in Figure 19. V_{ref} is the reference voltage at which the PV array is forced to operate. At the MPP, the reference voltage equals to V_{MPP} . Once the MPP is reached, the operation of the PV array is maintained at this point unless a change in ΔI is noted, indicating a change in atmospheric conditions and the MPP. The algorithm is decrementing or incrementing the reference voltage to track the new MPP. The increment size determines how fast the MPP is tracked. Fast tracking can be achieved with bigger increments but the system might not operate exactly at the MPP and oscillate about it instead; so there is a tradeoff. Similar MPPT schemes can be found in Park et al., (2006), Xiao and Dunford, (2004), Wolfs and Tang, (2005), and Liu et al., (2008). There are two main different variants of the IncCond method available in the literature. The IC method offers good performance under rapidly changing atmospheric conditions. The classic IncCond algorithm requires the same measurements in order to determine the perturbation direction: a measurement of the voltage V_{PV} and a measurement of the current I_{PV} . The Two-Model MPPT Control algorithm combines the CV and the classic IncCond algorithms; if

Figure 18. Flowchart of the CV method (Adapted from Dolara et al., 2009)

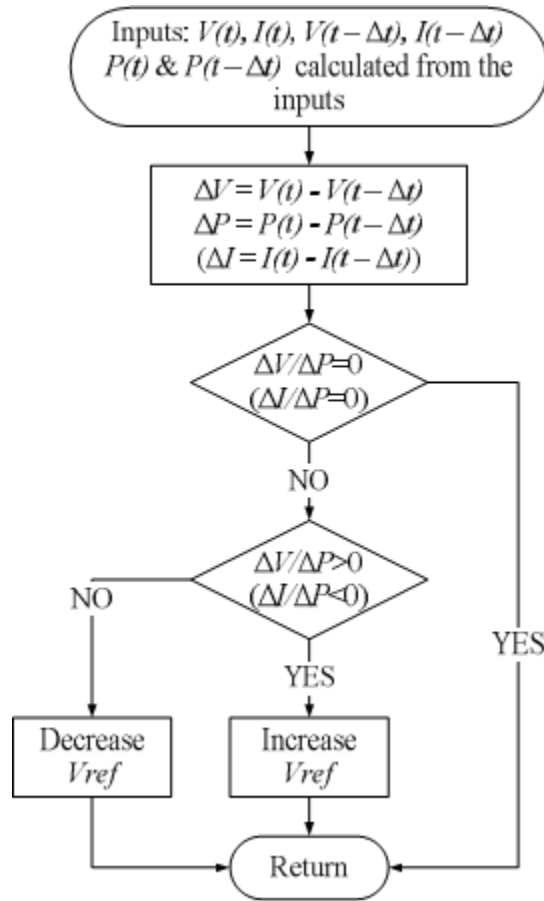


the irradiation is lower than 30% of the nominal level of the irradiance, the CV method is used, otherwise, the classic IncCond method is adopted. This method requires the solar irradiation S , as additional measurement.

It is well documented in the literature (Esrarn and Chapman, (2007)) that several maximum output power points arise in the PV system under non-uniform insolation. To overcome this problem, Irisawa et al., (2000) and Kobayashi et al. (2003) proposed a method that brings the operating point of the PV array close to the MPP in a first stage and then uses IncCond algorithm to exactly track the MPP in a second stage. In order to get the real peak output power point, the two-step MPPT control was proposed which is based on the combination of dV/dI method and the monitoring cell system. By proper control of the power converter, the initial operating point is set

to match a load resistance proportional to the ratio of the open-circuit voltage (V_{oc}) to the short-circuit current (I_{sc}) of the PV array. This two-stage alternative also ensures that the real MPP is tracked in case of multiple local maxima. It is shown in these papers that the proposed control method is effective under non-uniform insolation. The simulation results (Kobayashi et al. 2003) show that the response time of this control system is within 0.3 s even under the great change of insolation pattern. Koizumi and Kurokawa, (2005) uses a linear function to divide the I-V plane into two areas, one containing all the possible MPPs under changing atmospheric conditions. The proposed method takes full advantage of the known PV module characteristic. Identifying the domain without MPP, the operating point can rapidly approach the MPP using a linear function. In the neighborhood of the MPP, the algorithm is

Figure 19. The flow chart of incremental conductance (IncCond) MPPT algorithm



switched to a conventional IncCond method. The operating point is brought into this area and then IncCond is used to reach the MPP. The measured time taken for the approach to the MPP is reduced from 22% to 48% compared to the conventional algorithm. Against rapid radiation, reduction from 0.9 kW/m² to 0.8 kW/m² the response time is kept about the same to the IncCond algorithm. This method is quite simple so that it can be easily applied to not only IncCond method but also various MPPT algorithms. The linear function can be replaced to the higher order function.

Masri and Chan, (2010) proposed a new approach to design a boost converter for photovoltaic (PV) system using microcontroller.

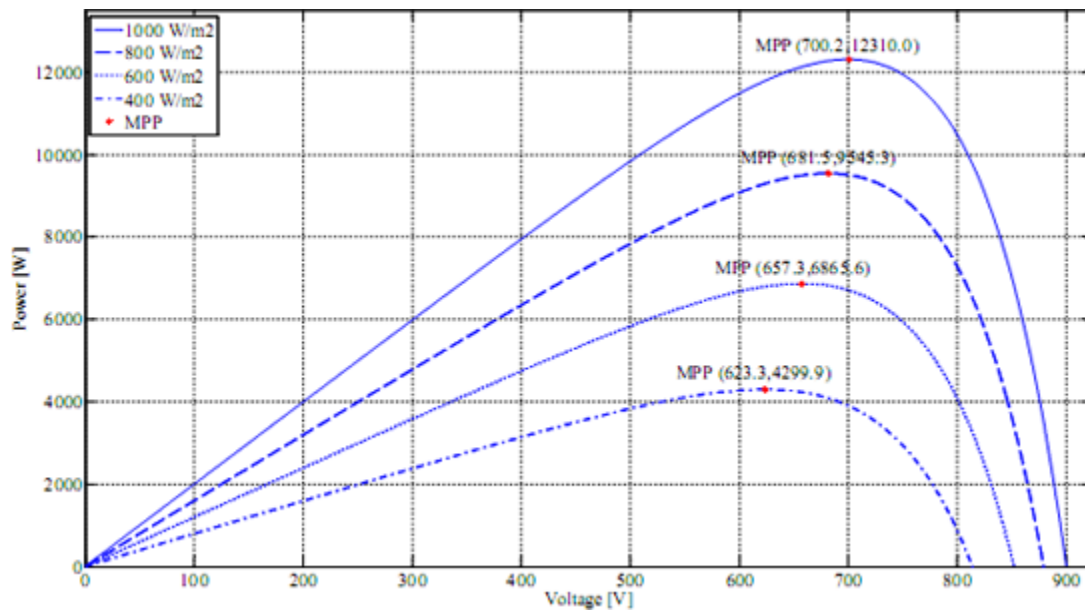
Microcontroller-based converter is chosen because it permits easy system modifications. The converter is simple, lightweight and small in size. Therefore, it can be attached to the solar panel as a single unit. Their MPPT algorithm is a modified version of the ones presented above. A less obvious, but effective way of performing the IncCond technique is to use the instantaneous conductance and the incremental conductance to generate an error signal (see for details Costoghe and Lindena, 1976):

$$err = \frac{I}{V} + \frac{dI}{dV} \quad (4)$$

It is a trivial task to prove that *err* goes to zero at the MPP. A simple proportional integral (PI) control can then be used to drive *err* to zero. Measurements of the instantaneous PV array voltage and current require two sensors. Harada and Zhao, (1993) proposed a novel MPPT based on the analysis of the characteristics of solar cells and Van Allen's multivibrator to control the output power of solar cells easily and to derive the maximum solar power simply and accurately according to the current load conditions. IncCond method lends itself well to DSP and microcontroller control, which can easily keep track of previous values of voltage and current and make all the decisions as per Figure 20. In both P&O and InCond schemes, how fast the MPP is reached depends on the size of the increment of the reference voltage.

There are two drawbacks of these techniques. The first and main one is that they can easily lose track of the MPP if the irradiation changes rapidly (Salas et al., 2006; Femia, 2008; Azevedo et al., 2009). In case of step changes, they track the MPP very well, because the change is instantaneous and the curve does not keep on changing. However, when the irradiation changes following a slope, the curve in which the algorithms are based changes continuously with the irradiation, as can be seen in Figure 19, so the changes in the

Figure 20. P-V curve depending on the irradiation



voltage and current are not only due to the perturbation of the voltage. Therefore, it is not possible for the algorithms to determine whether the change in the power is due to its own voltage increment or due to the change in the irradiation. The other handicap of both methods is the oscillations of the voltage and current around the MPP in the steady state (Veerachary et al., 2001, Jain and Agarwal, 2004, Salas et al., 2006). This is due to the fact that the control is discrete and the voltage and current are not constantly at the MPP but oscillating around it. The size of the oscillations depends on the size of the rate of change of the reference voltage. The greater it is, the higher is the amplitude of the oscillations. However, how fast the MPP is reached also depends on this rate of change and this dependence is inversely proportional to the size of the voltage increments. The traditional solution is a tradeoff, if the increment is small so that the oscillations decrease, then the MPP is reached slowly and vice versa, so a compromise solution has to be found.

To overcome these drawbacks, some solutions have been published in recent years. Regarding

the rapid change of the irradiation conditions, Sera et al., (2006a) and (2006b) developed an improved P&O algorithm, called “*dP-P&O*”, in which an additional measurement is performed without perturbation in the voltage and current. In this way, every three consecutive samples the effect of the perturbation in the voltage (current) and the effect of the change in the atmospheric conditions can be evaluated so that the increment in the power used in the algorithm only contains the effect caused purely by the MPPT algorithm. Then the correct decision about the direction of the next perturbation can be taken. The efficiency of the tracking is improved. A different solution is suggested in (Jain and Agarwal, (2004)), which considers the traditional P&O algorithm, in which the perturbation amplitude is tuned constantly taking into account the previous changes in the power. It also includes a stage in which the latest increment in the power is compared with the latest perturbation amplitude to determine if the power increment was due to a change in the irradiation. If this is the case, then the voltage perturbation is set to the same direction as the change in the

power condition. The steady state error and the tracking speed are improved, but the algorithm has only been tested with irradiation step changes and not with the irradiation slopes proposed in the European Standard EN 50530.

Fractional Open-Circuit Voltage and Short-Circuit Current MPPT Methods

The near linear relationship between V_{MPP} and V_{OC} of the PV array, under varying irradiance and temperature levels, has given rise to the fractional V_{OC} algorithm applied for PV MPPT systems (Masoum et al., 2002, Kobayashi et al., 2004), as:

$$V_{MPP} \approx k_1 V_{OC} \quad (5)$$

where k_1 is an empirical constant determined from the experimental data. Since k_1 is dependent on the characteristics of the PV array being used, it usually has to be computed beforehand by empirically determining V_{MPP} and V_{OC} for the specific PV array at different irradiance and temperature levels. The factor k_1 has been reported to be between 0.71 and 0.78. Once k_1 is known, V_{MPP} can be computed using Equation (5) with V_{OC} measured periodically by momentarily shutting down the power converter. Masoum et al., (2002) developed a detailed theoretical and experimental analyses for the comparison of two simple, fast and reliable maximum power-point tracking (MPPT) techniques for PV systems: the voltage-based (VMPPT) and the current-based (CMPPT) approaches. Two powerful and practical methods were proposed, investigated and compared in this study for MPPT of PV systems. They concluded that the optimal MPPT methodology strongly depends on matching load and tracker characteristics, considering the natural behavior, advantage, and limitations of CMPPT and VMPPT techniques.

However, the VMPPT and CMMPT methods incur some disadvantages, such as temporary loss of power. To prevent this, Kobayashi et al (2004)

suggested the use of pilot cells from which V_{OC} can be obtained. These pilot cells must be carefully chosen to closely represent the characteristics of the PV array. Kabayashi et al., (2004) claims that the voltage generated by the p-n junction diodes is approximately 75% of the open voltage. This eliminates the need for measuring V_{OC} and computing V_{MPP} . Once V_{MPP} has been approximated, a closed loop control on the array power converter can be used to asymptotically reach this desired voltage. Since Equation (5) is only an approximation, the PV array technically never operates at the MPP. Depending on the application of the PV system, this can sometimes be adequate. Even if fractional V_{OC} is not a true MPPT technique, it is very easy and cheap to implement as it does not necessarily require DSP or microcontroller control. However, Bekker and Beukes, (2004) pointed out that k_1 is no more valid in the presence of partial shading (which causes multiple local maxima) of the PV array and proposes sweeping the PV array voltage to update k_1 . This obviously adds to the implementation complexity and incurs more power loss.

On the other hand, the fractional short-circuit current I_{SC} results from the fact that, under varying atmospheric conditions, I_{MPP} is approximately linearly related to the I_{SC} of the PV array as shown in (Masoum et al., 2002, Mutoh et al., 2002, Kobayashi et al., 2004), and is given by:

$$I_{MPP} \approx k_2 I_{SC} \quad (6)$$

where k_2 is an empirical constant determined from the experimental data. Just like in the

fractional V_{OC} technique, k_2 has to be determined according to the PV array in use. The constant k_2 is generally found to be between 0.78 and 0.92. Measuring I_{SC} during operation is problematic. An additional switch usually has to be added to the power converter to periodically short the PV array so that I_{SC} can be measured using a current sensor. This increases the number

of components and cost. Yuvarajan and Xu, (2003) used a boost converter, in their CMPPT algorithm where the switch in the converter itself can be used to short the PV array. One have to keep in mind that power output is not only reduced when finding I_{sc} but also because the MPP is never perfectly matched as suggested by the Equation (6). One way of compensating k_2 such that the MPP is better tracked while atmospheric conditions change. To guarantee proper MPPT in the presence of multiple local maxima, Bekker and Beukes, (2004) suggested to periodically sweeping the PV array voltage from open-circuit to short-circuit to update k_2 . Most of the PV systems using fractional ISC in the literature use a DSP, while Yuvarajan and Xu, (2003) recommended instead the use of a simple current feedback control loop. Masoum and Savri, (2008) performed a comprehensive theoretical and experimental analysis to investigate the impact of array temperature on the performance of VMPPT and CMPPT techniques. Their major findings are: 1) the dependency of open-circuit voltage on array temperature is more than that of the short-circuit current; 2) the variation of insolation level has more impact on the short-circuit current than the open-circuit voltage; 3) in CMPPT techniques, variation of the current factor

$k_2 = I_{MPP} / I_{sc}$ with respect to temperature is linear and its slope and distance from the origin are constant under different insolation conditions; 4) in VMPPT techniques, variation of the voltage factor $k_1 = V_{MPP} / V_{oc}$ with respect to temperature is linear and slope of variation is approximately constant; and 5) the implementation of CMPPT method is more convenient due to less dependency on array temperature as compared with the VMPPT approach.

Ripple Correlation Control MPPT Methods

When a PV array is connected to a power converter, the switching action of the power converter imposes voltage and current ripple on the PV array.

Therefore, the PV array power is also subject to ripple. Ripple correlation control (RCC) (Midya et al., 1996) makes use of ripple, as an alternative to external operating point perturbation to perform MPPT. RCC correlates the time derivative of the time-varying PV array power dp/dt with the time derivative of the time-varying PV array current di/dt or voltage dv/dt to drive the power gradient to zero, thus reaching the MPP. Referring to Figure 1, if v or i is increasing ($dv/dt > 0$ or $di/dt > 0$) and p is increasing ($dp/dt > 0$), then the operating point is below the MPP ($V < V_{MPP}$ or $I < I_{MPP}$). On the other hand, if v or i is increasing and p is decreasing ($dp/dt < 0$), then the operating point is above the MPP ($V > V_{MPP}$ or $I < I_{MPP}$). Combining these observations, we see that $dp/dt * dv/dt$ or $dp/dt * di/dt$ are positive to the left of the MPP, negative to right of the MPP, and zero at the MPP. When the power converter is a boost converter (Midya et al., 1996), increasing the duty ratio increases the inductor current, which is the same as the PV array current, but decreases the PV array voltage. Therefore, the duty ratio control input is:

$$d(t) = -k_3 \int \frac{dp}{dt} \frac{dv}{dt} d\tau \quad (7)$$

or

$$d(t) = -k_3 \int \frac{dp}{dt} \frac{di}{dt} d\tau \quad (8)$$

where k_3 is a positive empirical constant. Controlling the duty ratio in this fashion assures that the MPP will be continuously tracked, making RCC a true MPP tracker. The derivatives in (7) and (8) are usually undesirable, but Midya et al., (1996) shows that AC-coupled measurements of the PV array current and voltage can be used instead since they contain the necessary phase information. High-pass filters can also be used to approximate the derivatives with cutoff frequency higher than the ripple frequency. A different and easy way of

obtaining the current derivative in (8) is to sense the inductor voltage, which is proportional to the current derivative. The non-idealities in the inductor have a small effect since the time constant of the inductor is much larger than the switching period in a practical converter. Esum and Chapman (2007) has been mentioned that $d(t)$ can fail due to the phase shift brought about by the intrinsic capacitance of the PV array at high switching frequencies. However, correlating power and voltage as in (7) is barely affected by the intrinsic capacitance. Simple and inexpensive circuits can be used to implement RCC (Midya et al., 1996). Performed tests show that RCC method accurately and quickly tracks the MPP, even under varying irradiance levels. The time taken to converge to the MPP is limited by the switching frequency of the power converter and the gain of the RCC circuit. Another advantage of the RCC methods is that it does not require any prior information about the PV array characteristics, making its adaptation to different PV systems straightforward.

There are several papers dedicated to the applications of the RCC MPPT methods or the ones that resemble to the RCC approach (see Esum and Chapman, 2007. Casadei et al., 2006) implemented a novel MPPT scheme for single-phase grid-connected PV systems employing an embedded MPPT algorithm able to find the maximum power point by computing the sign of the PV power derivative versus voltage. This computation exploits PV current and voltage oscillations, at a frequency twice than that of the grid, due to the connection of the converter with a single-phase grid. The proposed MPPT algorithm does not require knowledge of the model of the PV panels. Once the MPPT algorithm has computed the power derivative, the dc link voltage regulator drives the PV panels' voltage toward the MPP value. The current regulator ensures steady-state sinusoidal current and unity power factor, even in the presence of grid voltage perturbations. Simulation and experimental results in both steady state and dynamic conditions shown good performance of

this control system and confirm the effectiveness of the proposed PV generation system for any operating condition. A dynamically rapid RCC-based method for tracking the MPP of PV arrays was studied by Esum et al., (2006). The algorithm was verified against the experiment. The technique takes advantage of the signal ripple, which is automatically present in power converters. In this method, the ripple is interpreted as a perturbation from which a gradient ascent optimization can be realized. The technique converges asymptotically at maximum speed to the maximum power point without the benefit of any array parameters or measurements. The technique has also simple circuit implementations.

Kimball and Krein, (2008) extended the RCC-based MPPT algorithm from the previous analog technique to the digital domain. The proposed digital implementation is less expensive, more flexible, and more robust. With a few simplifications, the RCC method is reduced to a sampling problem; that is, if the appropriate variables are sampled at the correct times, the discrete-time RCC (DRCC) algorithm can quickly find the optimal operating point. Although the new method superficially resembles conventional techniques like P&O, DRCC can reach true steady-state and uses only ripple information that is readily available in any switching power converter. A mode-switching algorithm that used the fractional V_{oc} method for periodic re-initialization improved robustness and ensured that the MPPT would converge to the global maximum power point. Tracking accuracy exceeded 98% for direct insolation with this method, while an update rate of more than 1 kHz enabled the system to track maximum power on the time scale of milliseconds.

Kroeger et al., (2010) proposed a digital implementation of ripple correlation control based on a continuous-time analog formulation was presented. The performance of the method was examined in experiments. The results showed the addition of a lead compensator to account for the impact of panel capacitance and wire induc-

tance. This simple digital implementation is user friendly and allows for use of centralized control and monitoring of multiple MPPTs in multi-panel installations. Spiazzi et al., (2010) discussed and compared three maximum power point tracking (MPPT) techniques: voltage linear reference, ripple correlation and incremental and mirrored conductance (IMC). Their minimum complexity makes them ideal candidates for low cost on-chip integration and suggests their employment in photovoltaic (PV) module applications. The basic operating principle, the main limitations and the expected effectiveness of each technique are illustrated. Experimental verification of the attainable performance from proof of concept circuit implementations and a comparison of the expected performance and circuit complexity have been presented. The outcome shows for each of the techniques the need to trade-off simplicity against some inherent limitation (reduced effectiveness, sensitivity to parasitic components, limit cycle oscillations respectively). Overall, the IMC method seems to represent the best candidate for integration in PV module converter applications.

An exponential adaptive perturb and observe algorithm (EAPO) for real-time optimization of dynamic systems was developed by Buyukdegirmenci et al., (2010). In this paper, other adaptive methods are reviewed and compared. Convergence and stability are discussed, while the design requirements for applying EAPO are also addressed in an example for impedance matching. The proposed EAPO is compared to two prior real-time optimization techniques: conventional perturb and observe algorithm (P&O), and ripple correlation control (RCC). The method is shown to track the optimum with lower amplitude oscillations than P&O in the context of maximum power point tracking (MPPT) of a photovoltaic array. It is also compared to RCC in several applications including MPPT, impedance matching, and loss minimization of a separately excited DC machine. Simulations and experiments show that the proposed EAPO achieves maximum power

transfer with less than 4% error. Over all, the steady-state error and tracking response of the proposed EAPO are shown to be similar to RCC.

Temperature Methods

The open-circuit voltage V_{OC} of the solar cell varies mainly with the cell temperature, whereas the short-circuit current is directly proportional to the irradiance level, and is relatively steady over cell temperature changes. The open-circuit voltage V_{OC} is function cell temperature and the open-circuit voltage under standard test conditions (STC) (see Faranda and Leva, 2008). However, the optimal voltage can be described by the following equation:

$$V_{OP} \cong f(S, T) \cdot V_{MPP,STC} \quad (9)$$

where $V_{MPP,STC}$ is the MPP voltage under STC, and S is the irradiance level. There are two different temperature methods available in the literature. The temperature gradient (TG) algorithm uses the temperature T to determine the open-circuit voltage V_{OC} from the solar cell equations. The optimum operating voltage V_{op} is then determined as in the open circuit voltage technique, avoiding power losses. TG requires the measurement of the temperature T and a measurement of the voltage V_{PV} for the PI regulator. The temperature parametric (TP) equation method adopts Equation (9) and determines the optimum operating voltage V_{op} instantaneously by measuring T and S . The TP method requires also the measurement of solar irradiance S .

MPPT ALGORITHMS AND METHODS USING ARTIFICIAL INTELLIGENCE TECHNIQUES

Microcontrollers have made possible the use of the fuzzy logic control techniques for PV system MPPT over the last decades (Hilloowala and Sharaf, 1992, Won et al., 1994, Senjyu and

Uezato, 1994, and Simoes et al., 1998). Simoes et al. (1998) studied the analysis, modeling and implementation of a fuzzy based photovoltaic peak power tracking system. The solar panel is integrated with the converter model and a fuzzy algorithm is developed to perform an on-line search procedure to track the maximum power continuously. An inexpensive RISC microcontroller implemented the system. Experimental results have shown excellent performance, robustness with parameter variation, modularity for parallel operation at higher power, ready to retrofit existing installations. Veerachary et al., (2003) emphasized that the fuzzy logic controllers have the advantages of working with imprecise inputs, not needing an accurate mathematical model, and handling nonlinearity. Moreover, the fuzzy control improves the tracking performance compared to the conventional PI controller and, thus, avoids the tuning of controller parameters. Furthermore, use of coupling among the inductor branches improves the steady-state performance without deteriorating the dynamic performance. Finally yet importantly, the simulation and experimental results demonstrated the peak power tracking capability of the proposed fuzzy logic-based schemes.

Fuzzy logic controller (FLC) generally consists of three stages: fuzzification, rule base table lookup, and defuzzification (Simoes et al., 1998, Wilamowski and Li, 2002). During fuzzification, numerical input variables are converted into linguistic variables based on a membership function similar to Figure 21. In this case, five fuzzy levels are used: NB (Negative Big), NS (Negative Small), ZE (Zero), PS (Positive Small), and PB (Positive Big). Mahmoud et al. (2000) and Patcharaprakiti and Premrudeepreechacharn, (2002) used seven fuzzy levels, to improve the accuracy. The simulation and experimental results of these implementation show adequate and robust performance for the proposed FLC in terms of settling time, overshoot and steady state error with the PV system. In Figure 21, the parameters a and b are based on the range of values of the

numerical variable. The membership function maybe sometimes made less symmetric to give more importance to specific fuzzy levels as proposed by Hilloowala and Sharaf, (1992), Simoes et al., (1998) and Veerachary et al., (2003). These membership functions are denser at the center and, thus, provide more sensitivity against variation in the solar cell array terminal voltage (Veerachary et al., (2003)). This occurs particularly in cases where the change in the terminal voltage tends to zero. The inputs to a MPPT fuzzy logic controller are usually an error E and a change in error ΔE . The user has the flexibility of choosing how to compute E and ΔE . Since dP/dV is zero at the MPP, Hilloowala and Sharaf, (1992) and Khaehintung et al., (2004) and (2005) used the approximation:

$$E(n) = \frac{P(n) - P(n-1)}{V(n) - V(n-1)} \quad (10)$$

and

$$\Delta E(n) = E(n) - E(n-1) \quad (11)$$

Equivalently, equation (10) is very often used. Once E and ΔE are calculated and converted to the linguistic variables, the fuzzy logic controller output, which is typically a change in duty ratio ΔD of the power converter, can be looked up in a rule base table (Veerachary et al., 2003, Khaehintung et al., 2004 and 2005). The linguistic variables assigned to ΔD for the different combinations of the E and ΔE are based on the power converter being used and on the knowledge of the user. If for example, the operating point is far to the left of the MPP (see Figure 12 for details), that is E is PB, and ΔE is ZE, then we want to largely increase the duty ratio that is ΔD should be PB to reach the MPP. In the defuzzification stage, the fuzzy logic controller output is converted from a linguistic variable to a numerical variable still using a membership function as in Figure 21.

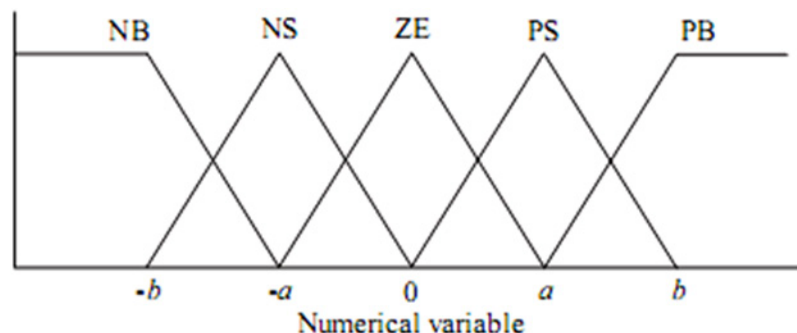
This provides an analog signal that will control the power converter to the MPP.

Khachintung et al., (2004) and (2005) investigated the application of self-organizing fuzzy logic controller (SOFLC) for maximum power point tracking the grid-connected PV system. In their design, a boost converter is used in the system to deliver the output from the solar array to DC-AC inverter, and feed the power into the AC grid. The duty ratio for the operation of the boost converter is optimally adjusted in such a way that the maximum power point, which normally varies according to the environment, can be achieved. The simulation results confirm that the proposed SOFLC has improved the speed and the transient response of the maximum power point tracking of a PV array. This leads to fast settling time of the response for the DC-DC converter to capture the utility DC bus voltage, and the power conversion operation of the DC-AC inverter. The proposed technique can be easily realized by means of a look-up table. It therefore offers a cost-effective approach for real time MPPT implementation. D'Souza et al., (2005) and (2006) studied the implementation of hybrid (P&O and FLC) MPPT algorithms, allowing the use of smaller perturbations, reducing the power oscillation around the MPP and increasing the power yield in the steady-state without compromising the transient response. The use of variable size perturbations based on Fuzzy logic further reduced the power oscillations

around the MPP. An asymmetrical membership functions are also used in this implementations.

MPPT fuzzy logic controllers have been shown to perform well under varying atmospheric conditions. However, their effectiveness depends a lot on the knowledge of the user or control engineer in choosing the right error computation and coming up with the rule base table. Patcharaprakiti and Premrudeepreechacharn, (2002) suggested the use of an adaptive fuzzy logic control that constantly tunes the membership functions and the rule base table so that optimum performance is achieved. Experimental results from shown fast convergence to the MPP and minimal fluctuation about it. While Veerachary et al., (2003) empirically uses two different membership functions to show that the tracking performance depends on the type membership functions considered. An offline ANN, trained using the back-propagation algorithm, was utilized for online estimation of reference voltage in the feed-forward loop. Simulation and experimental results demonstrated the peak power tracking capability of the proposed scheme. It was also demonstrated that the fuzzy control improves the tracking performance compared to the conventional PI controller and, thus, avoids the tuning of controller parameters. Furthermore, use of coupling among the inductor branches improves the steady-state performance without deteriorating the dynamic performance. Taherbaneh et al., (2007) proposed a combination

Figure 21. Membership function for inputs and output of fuzzy logic controller



of fuzzy-based MPP tracking and fuzzy-based sun tracking in order to maximize the PV system generated power. Based on the experimental tests they concluded that the combined implementation of fuzzy-based MPP tracking and fuzzy-based sun tracking simultaneously, the panel output power could be remarkably increased leading in turn to the reduction of the size, weight and cost of PV systems. Karlis et al., (2007) presented a novel MPPT method based on fuzzy cognitive networks (FCN). The new method gives a good maximum power operation of any PV array under different conditions such as changing insolation and temperature. FCNs can model dynamical complex systems that change with time following nonlinear laws. Moreover, they can operate in continuous interaction with the physical system they represent and adapt their knowledge based on training data. The efficiency of the proposed algorithm has been studied for identifying the maximum operating point for the real time MPPT control of PV modules. The FCN was off-line trained using appropriately constructed data. With this training the FCN is appropriate to operate with any PV system under changing climatic conditions. When tested with a specific PV system gave accurate predictions under different conditions such as changing insolation and temperature. The accuracy is not degraded due to seasonal variations.

Thiagarajan et al., (2008) proposed an adaptive fuzzy controller, combined with a DC-DC boost converter to improve the performances of PV systems in standalone or grid-connected mode of operations. The above system is analyzed with variation in temperature of PV cell and variation in the load parameters for the feasibility of the designed controller. It is found that the controller developed provides fast responses and good performance. Atlas and Sharaf, (2008) developed a novel and simple on-line fuzzy logic-based dynamic search, detection and tracking controller to ensure MPP operation of a PV system under excursions in solar insolation, ambient temperature and electric load variations. The proposed MPP

search and detection algorithm is fully dynamic in nature and operates without any required direct measurement or forecasted PV array information about the irradiation and temperature. An added Search sensitivity measure is defined and is used in the MPP search algorithm to sense and dynamic response for other reduced MPP operating points. The proposed dual action control scheme is very effective for large PV array installations using only the measurements of common stand-alone photovoltaic array current and voltage signals. The proposed novel dynamic FLC controller uses the power error and the ratio $\Delta P/\Delta I$ as the two input signals instead of using error signal and its change over one sampling period. The rule generation philosophy of this approach differs from that of a usual FLC structure. The auxiliary part of the dual fuzzy MPP tracking controller is introduced as a novel approach to handle the dead zones left from the main part. The proposed MPP detection algorithm and dual fuzzy logic MPP tracking controller are tested using the MATLAB/Simulink software environment by digitally simulating the PV array scheme feeding hybrid DC loads.

Zhang and Zhao, (2009) in order to minimize the inherent oscillations of the P&O MPPT algorithms employed a novel asymmetric fuzzy control method, which adjusts the perturbation step according to the PV module work to reduce the power oscillation. An asymmetric fuzzy control was selected in this study, which has input variable that can reflect working point of PV module exactly, and membership function and fuzzy rules are designed to make fuzzy controller can adjust the perturbation according to working point of PV module. Experimental results have shown that the proposed method can track MPP rapidly under solar insolation changing and reduce significantly the power oscillations. Zeng and Liu, (2009) proposed an intelligent fuzzy method for MPPT of PV systems. A quick tracking can be done by inference engine expressed by equations with adaptive factor, while no memory space for fuzzy rules table was employed in this implementation,

instead of fuzzy rules lookup table, which saves memory space and accelerates operation process. It is simple to be implemented on single chip. The availability and adjustability of this method is validated by experiments using PV arrays, boost converter and single-phase grid-connected inverter. The simulation and experiment results showed its attractive features such as simplicity, fast response, well dynamic performance and that it can increase output power extracted from PV arrays. In addition, the experiment results show that more power has been extracted from the PV arrays with this method and output holds stable, though its hardware cost is low comparing to those with other methods. In order to overcome the drawbacks of the traditional MPPT methods, Jiang and Wang, (2009) considered the application of a fuzzy support vector machine (FSVM) regression to predict the output voltage of photovoltaic components MPP. Cross-validation and the steepest descent were used to determine the best parameters of the regression model of support vector machine. The prediction model of output voltage is based on the open circuit voltage and the parameters time of MPP. From comparative analysis of results shows that the FSVM methods have higher accuracy, stability, and has a very good basis of mathematical theory than neural network method. Therefore, using the method of support vector machine to predict the MPPT have good application prospects.

Ammasai Gounden et al., (2009) have developed a fuzzy logic controller, for the first time for interfacing PV array with utility grid through a three-phase line-commutated inverter. The controller tracks and feeds maximum power to the utility grid. The linguistic variables have been selected appropriately to modulate the firing angle of the inverter for tracking the maximum power. The MATLAB/Simulink model of the proposed scheme employing fuzzy logic controller has been built using MATLAB/PSB. The comparison of experimental and simulation results shows very close agreement between the two thus validat-

ing the controller proposed. Diaz et al. (2010) studied an intelligent fuzzy method for maximum power point tracking of a single grid-connected PV system. The proposed MPPT fuzzy method is improved by weighting the control action by the short-circuit current, via an estimator of the short-circuit current based on a Takagi-Sugeno (T-S) fuzzy model of the PV generator. The short-circuit current can be estimated under any weather condition in real time, without disconnecting the photovoltaic generator and measuring it. Simulation results show attractive features such as, accuracy, fast response, good dynamic performance and efficiency in the conversion process.

Jiang et al., (2010) developed an adaptive mechanism and control for the MPPT method based on fuzzy logic, which includes automatic parameter tuning and directly uses the DC-DC converter duty cycle as a control parameter. The verification was performed in MATLAB/Simulink. Simulation results show that PV power generation system, which applies fuzzy control, can fast and efficiently track the maximum power point of PV solar array. Chiu et al., (2010) developed a T-S fuzzy model based maximum power control to enhance the efficiency of the solar PV systems. To draw the maximum power from a solar PV array, a buck converter is applied to adjust the output of PV power. Based on the T-S fuzzy representation, the fuzzy maximum power point tracking (MPPT) controller was developed to maintain the maximum power voltage. The MPPT control is achieved with asymptotic convergence, while control gains can be systematically designed by solving linear matrix inequality (LMI). Furthermore, the robust MPPT is also discussed to cope with varying atmosphere and system uncertainty. The advantages of the proposed controller include: i) the calculation of the maximum power operational point is not required; ii) a controller redesign is not needed even if the insolation and temperature of the PV array are changed; iii) the robust MPPT control is guaranteed when considering uncertainty; and iv) the design is more

systematic than traditional methods. In addition, the overall stability has strict analysis, which is lacked in traditional methods. Satisfactory performance is shown from the numerical simulation and experimental results.

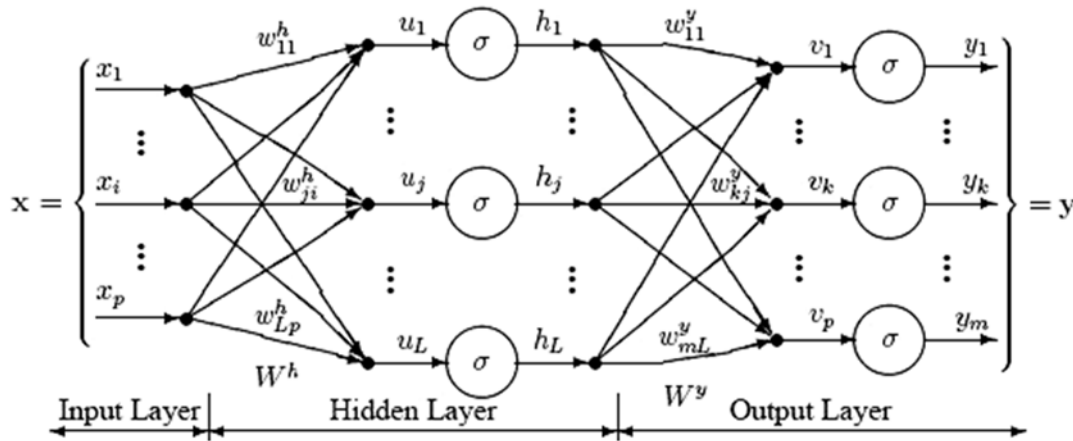
Fuzzy-based MPPT control to cope with the drawbacks associated with traditional MPPT approaches due to the changing atmospheric conditions and oscillations around MPP were proposed and studied, during the last decade by several authors. Among others, Petreus et al., (2010), implemented fuzzy MPPT control to overcome the PV power fluctuations due to changing of luminosity, while Subiyanto et al., (2010) implemented a hardware prototype of such fuzzy logic MPPT controller. Chiu and Ouyang, (2011) used a unified T-S fuzzy model-based maximum power control approach to enhance the efficiency and robustness of the solar photovoltaic power generation. By using the T-S fuzzy model, the fuzzy maximum power voltage (MPV)-based and direct maximum power control schemes were realized in the same design form. The asymptotic MPPT and gain criterion performance to disturbance and rapidly changing atmosphere are achieved even if considering partial state feedback and parametric uncertainty. Furthermore, the controller and observer gains are able to be solved and adjusted separately by the new linear matrix inequality formulation. Other advantages of the proposed control method include: 1) no coordinate transformation and no calculation of the maximum power operational point is required; 2) the overall stability has strict analysis, which is lacked in traditional methods; and 3) better control performance is obtained in comparison with the traditional methods from theoretical analysis and experiments.

The advent of microcontrollers makes possible the MPPT fuzzy logic controllers. The neural networks (Hiyama et al., 1995, Hussein, 2002; Mellit and Kalogirou, 2008), are well adapted for microcontrollers. Artificial neural networks consist of an input layer, one or more hidden layer(s), and an output layer. However, the most

common ANN configuration consists of three-layer structure as shown in Figure 22. The number nodes in each layer vary and are user-dependent. The input variables can be PV array parameters like V_{oc} and I_{sc} , atmospheric data like irradiance and temperature, or any combination of these. The output is usually one or several reference signal(s) like a duty cycle used to drive the power converter to operate at or close to the MPP. How close the operating point gets to the MPP depends on the algorithms used by the hidden layer and how well the neural network is trained. The links between the nodes are all weighted (Figure 22). To identify accurately the MPP, the weights have to be carefully determined through the training process, usually over long periods. The most used algorithm for training is the so-called back-propagation (B-P), referred also as supervised training. The B-P training algorithm needs only inputs and the desired output to adapt the weight. This method performs a gradient descent on the error surface to minimize the error function. Since most PV arrays have different characteristics, a neural network has to be trained specifically for a PV array with which it will be used. The characteristics of a PV array also change with time, implying that the neural network has to be trained periodically to guarantee accurate MPPT.

Giraud and Salameh, (1999) used a combined radial-basis-functions (RBF) and B-P network to predict the effects of passing clouds on a grid-connected PV system with battery storage. In this method the irradiance as input signal, the neural network models the effects of random cloud movement on the electrical variables of the MPPT and the variables of the utility-linked inverter over a short period. During this short time interval, the irradiance is considered as the only varying input parameter affecting the electrical variables of the system. The advantages of ANN simulation over standard model is that it does not require the knowledge of the internal system parameters, involves less computational effort, and offers a compact solution for multiple-variable problems.

Figure 22. Example of neural network architecture



Al-Amoudi and Zhang, (2000) proposed a neural network-based approach for solar array modeling. The logic-hidden unit of the proposed network consists of a set of nonlinear radial basis functions (RBFs) which are connected directly to the input vector. The links between hidden and output units are linear. The model can be trained using a random set of data collected from a real photovoltaic (PV) plant. The training procedures are fast and the accuracy of the trained models is comparable with that of the conventional model. The principle and training procedures of the RBF-network modeling when applied to emulate the I - V characteristics of PV arrays are discussed. Simulation results of the trained RBF networks for modeling a PV array and predicting the maximum power points of a real PV are given. This RBFN-based scheme can be used to predict the reference voltages on-line or the power conditioners of any PV-grid connected systems. The well-accepted fact that in the grid connected photovoltaic (PV) systems, the MPPT algorithm plays an important role in optimizing the solar energy efficiency led Lee et al., (2010) to develop a new ANN-based MPPT method for searching MPP fast and exactly. For the first time, a combined the ANN-based PV model method and incremental conductance method was pro-

posed. The advantage of ANN-based PV model method is the fast MPP approximation based on the ability of ANN according the parameters of PV array that used. The advantage of IncCond method is the ability to search the exactly MPP based on the feedback voltage and current without caring the characteristics of the PV array. While the ANN decreases the tracking time of the IncCond algorithm, the IncCond tracks the exact MPP and helps ANN not be trained periodically. The simulation implemented in MATLAB.

Zhang et al., (2002) studied a novel genetic algorithm trained radial basis function neural network (GA-RBFNN)-based model to carry out the MPPT control for grid-connected PV power generation control systems. The hidden layer of the ANN is self-organized by the GA-based RBF growing algorithm. The trained GA-RBFNN-based MPP model is then employed to predict the MPPs of a PV array using measured environmental data. The simulation results are compared with the conventional P&O method can track the maximum power points more promptly and accurately in response to a change in weather condition. Thus, it can give higher energy collection efficiency. The main benefit in using the GARBFNN is that one can treat a PV array as a black box, and a MPP model can be obtained without having any prior

knowledge of the physical parameters relating to the PV panel studied. A new MPPT methodology was applied to a grid-connected photovoltaic system based on a novel neuro-fuzzy estimator was developed by Chaouachi et al., (2010). The whole system was simulated under MATLAB/Simulink environment. In this study, the developed neuro-fuzzy network consists of two stages; the first one is a fuzzy rule-based classifier, the second one is composed of three multi-layered feed forwarded ANNs trained offline using experimental data from a real PV system installed at the engineering campus of Tokyo University of Agriculture and Technology. The proposed neuro-fuzzy estimator showed the ability to faithfully emulate the dynamic and nonlinear behavior of a photovoltaic generator under a large wide of climatic conditions. In fact the multi-model aspect of the proposed machine learning confer it a distinct generalization ability comparing to a conventional single ANN-based MPP predictor. Maximum power operation was achieved by tracking the reference voltage estimated by the neuro-fuzzy network through a DC–DC converter. The completely grid-connected system performance was tested during a cloudy day with several rapid irradiance variations. The simulation results showed that the proposed system performances was not degraded, as the MPPT dispositive was able to track the reference voltage insuring an optimal operating condition under any rapid changing meteoric conditions.

A controller consisting of an ANN MPPT tracker and the optimal control unit for a PV system was developed by Rai et al., (2011). The ANN tracker estimates the voltages and currents corresponding to a maximum power delivered by solar PV array for variable cell temperature and solar radiation (Figure 23). In this approach, the cell temperature is considered as a function of ambient air temperature, wind speed and solar radiation. The proposed ANN-based MMPT is trained employing a set of 124 patterns using the back propagation algorithm. The peak power tracking capabilities of the proposed scheme based

on ANN-based maximum power point tracking controller is demonstrated through simulated and experimental results. The simulated results show that the ANN based controller in its maximum power point tracking performance excels over the conventional PID controller and avoids the tuning of controller parameters. Ben

Salah and Quali, (2011) performed a comparative study of two MPPT methods, one using a fuzzy logic approach and the other one using a neural network controller. These proposed algorithms in FL and ANN consist in commanding a boost DC–DC inverter to obtain the MPPT directly from the climate data solar radiation and PV cell temperature. The approaches are validated on an experimental setting connected to a 24V DC load. The new methods give a good maximum power operation of any photovoltaic array under different conditions such as changing solar radiation and PV cell temperature. From the simulation and experimental results, the fuzzy logic controller can deliver more power than the ANN-based one. However, both can generate more power than other methods found in literature

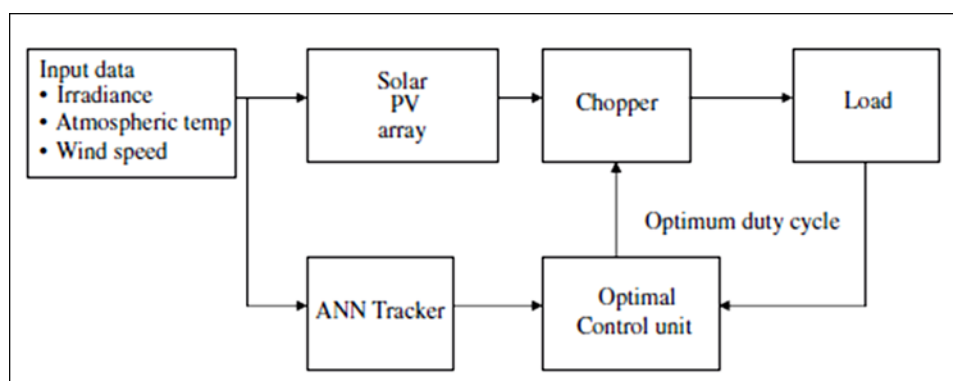
OTHER MPPT TECHNIQUES

Current Sweep MPPT Methods

The current sweep MPPT method (Budur and Ermis, 1994) uses a sweep waveform for the PV array current such that the PV array I–V characteristic is obtained and updated at fixed time intervals. The V_{MPP} can then be computed from the characteristic curve at the same intervals. The function chosen for the sweep waveform is directly proportional to its derivative. The PV array power can be expressed as $p(t) = v(t) \cdot f(t)$, and the MPP the power derivative is zero:

$$\frac{dp(t)}{dt} = \left[v(t) + k_4 \frac{dv(t)}{dt} \right] \frac{df(t)}{dt} = 0 \quad (12)$$

Figure 23. Schematic diagram of ANN controlled PV system (Adapted from Rai et al., 2011)



The differential equation in (12) has the following solution:

$$f(t) = I_{\max} \cdot \exp\left(-\frac{t}{\tau}\right) \quad (13)$$

The current in (12) can be easily obtained by using some current discharging through a capacitor. Since the derivative of (13) is nonzero, (12) can be divided throughout by $df(t)/dt$ and, with $f(t) = i(t)$, (12) simplifies to this differential equation:

$$\frac{dp(t)}{dt} = v(t) + k_4 \frac{dv(t)}{dt} = 0 \quad (14)$$

Once V_{MPP} is computed after the current sweep, (14) can be used to double check whether the MPP has been reached. Budur and Ermis, (1994) implemented this algorithm through analog computation. The current sweep takes about 50 ms, implying some loss of available power. However, this MPPT technique is only feasible if the power consumption of the tracking unit is lower than the increase in power that it can bring to the entire PV system. The proposed method was implemented on a 250 W photovoltaic solar panel successfully. In the experimental setup, a sleep mode is also implemented to minimize the energy loss of the

chopper when the panel output power becomes less than a preset power value.

$$P_{PV} = aV_{PV}^3 + bV_{PV}^2 + cV_{PV} + d \quad (15)$$

This process should be repeated every few milliseconds in order to find a fine MPP. The accuracy will depend on the number of samples. The disadvantage of this method is that either it requires accurate knowledge of the physical parameters relating to the cell material or manufacturing specifications or the expressions used are not valid for all climatological conditions. In addition, it might require a large memory capacity for calculation of the mathematical formulations.

DC Link Capacitor Droop Control

DC link capacitor droop control (Kitano et al., 2001) is a MPPT technique that is designed to work with a PV systems connected in parallel with an AC system line. The duty ratio of an ideal boost DC-DC converter is given by:

$$d = 1 - \frac{V}{V_{\text{link}}} \quad (16)$$

where V is the voltage across the PV array and V_{link} is the voltage across the DC link. If V_{link} is

kept constant, increasing the current going in the inverter increases the power coming out of the boost converter and consequently increases the output power of the PV array. While the current is increasing, the voltage V_{link} is kept constant as long as the power required by the inverter does not exceed the maximum power available from the PV array. If that is not the case, V_{link} starts drooping. Right before that point, the current control command I_{peak} of the inverter is at its maximum and the PV array operates at the MPP. The AC system line current is fed back to prevent V_{link} from drooping and d is optimized to bring I_{peak} to its maximum, achieving MPPT.

DC link capacitor droop control does not require the computation of the PV array power, but according to Kitano et al., (2001), its response deteriorates when compared to a method that detects the power directly; this is because its response directly depends on the response of the dc voltage control loop of the inverter. This control scheme can be implemented easily with analog operational amplifiers and decision-making logic units.

Load Current or Load Voltage Maximization

The purpose of MPPT techniques is to maximize the power coming out of a PV array. When the PV array is connected to a power converter, maximizing the PV array power also maximizes the output power at the load of the converter. Maximizing the output power of the converter maximizes also the PV array power output (Enslin and Snyman, 1992, Arias et al., 2004), assuming a lossless converter. It is well known that most of the loads are voltage-source type, current-source type, resistive type, or a combination of these. For a voltage-source type load, the load current i_{out} should be maximized to reach the maximum output power. For a current-source type load, the load voltage v_{out} should be maximized. For the other load types, either i_{out} or v_{out} can be used. This is also true for nonlinear load types as

long as they do not exhibit negative impedance characteristics. Therefore, for almost all loads of interest, it is adequate to maximize either the load current or the load voltage to maximize the load power. Consequently, only one sensor is needed.

dP/dV or dP/dI Feedback Control MPPT Techniques

With the capabilities of the DSP technique and microcontroller being able to handle complex computations, an obvious way of performing MPPT is to compute the slope (dP/dV or dP/dI) of the PV power curve (see Figure 12) and feed it back to the power converter with some control to drive it to zero (Shmilovitz, 2005). The way the slope is computed differs from paper to paper. Bhide and Bhat, (1992) proposed a new algorithm to compute the derivative dP/dV , stores its sign for the past few cycles, and used on the stored signs to either to increment or decrement the duty ratio of the power converter to reach the MPP. A dynamic step size is usually used to improve the transient response of the system. In a similar approach Sugimoto and Dong, (1997) used a linearization-based method to compute dP/dV . Other approaches used sampling and data conversion algorithms with subsequent digital division of power and voltage to approximate dP/dV (Chiang et al., (1998)). Conventionally, PV energy conversion systems are composed of a DC-DC converter, a DC-AC inverter, batteries, and a center-tapped output transformer (Sera et al., 2006a, 2006b, Teodorescu et al., 2011). The efficiency of such series-connected multi-stage devices is low. Further, the size is large and the weight is high. To overcome these drawbacks Kuo et al., (2001) proposed a new approach. A novel single-stage MPPT controller is used for rapid tracking of the PV array's MPP. The proposed design, by contrast, uses a single-stage configuration, thus increasing efficiency and reducing size. In addition, the proposed system operates as power supply on sunny days and operates as

an active power line conditioner at low or zero insolation. Hence, the proposed PV energy conversion system provides useful function in any weather, significantly enhancing system utility. Using the slope of power vs. voltage of a PV array, the proposed MPPT controller allows the conversion system to track the maximum power point very rapidly. As opposed to conventional two-stage designs, a single-stage configuration is implemented, resulting in size and weight reduction and increased efficiency. Figure 23 is showing the single-stage PV system. The proposed system acts as a solar generator on sunny days, in addition to working as an active power line conditioner on rainy days. The simulations and experimental results demonstrate the superior performance of the proposed technique. The proposed algorithm reduces oscillation, resulting in significantly improved tracking.

Other MPPT techniques and methods include, among others: the array reconfiguration, linear current control, the computation of the I_{MPP} and V_{MPP} involving the irradiance and temperature levels or state space models. El-Shibini and Rakha, (1989) proposed the arrangements of the PV arrays in different series and parallel combinations such that the resulting MPPs meet specific load requirements. This method is time consuming and tracking MPP in real time is not obvious. A linear current control employing the fact that there is a linear relationship between I_{MPP} and the level of irradiance was developed by Pan et al. (1999). The current I_{MPP} is found by sensing the irradiance level and a PI controller is used such that the PV array current follows I_{MPP} . The I_{MPP} and V_{MPP} can be computed from equations involving temperature and irradiance levels, which are not usually easy to measure, as used in the algorithm developed by Takashima et al., (2000). Once I_{MPP} or V_{MPP} is obtained, feedback control is used to force the PV array to operate at the MPP. A state-based MPPT algorithm was introduced by Solodovnik et al., (2004). A state space model, in this approach, represents the PV system while a nonlinear time-

varying dynamic feedback controller tracks the MPP. Simulations confirmed that this technique is robust and insensitive to changes in system parameters and that the MPPT is achieved even with changing atmospheric conditions and in the presence of multiple local maxima caused by partially shaded PV array or damaged cells. However, no experimental tests of the method validity were conducted. The common PV power electronics topologies consist of two power stages (usually a DC-DC converter followed by an inverter). A single-stage inverter that performs both MPPT and output current Solodovnik et al., (2004), developed regulation for the utility grid distribution. Based on the voltage of the PV array, one-cycle control is used to adjust the output current of the single-stage inverter such that MPPT is attained. The control circuit consists of an inexpensive DSP system. Operation is shown to be close to the MPP throughout a daytime period. The slight discrepancy is due to the inability of the controller to account for temperature variation.

Masoum et al., (2002) proposed microprocessor-controlled tracker capable of online voltage and current measurements and programmed with V_{MPP} and I_{MPP} algorithms. Considering the natural behavior, these researchers for some typical PV loads made advantage, and limitations of the IMPP and VMPP techniques, the following suggestions. The PV loads that require low-voltage and high-current outputs (e.g., battery chargers and low-resistance loads), are best matched with the VMPP system and result in better overall performance (cost, efficiency, and noise). While the PV loads with high voltage and low current (e.g., motors and high resistive loads) could be matched with either V_{MPP} or I_{MPP} systems, but first technique will result in simple hardware with higher efficiency and lower noise and cost. Statistical data relevant to irradiance and temperature levels are collected over a period of one year or longer, together with the best fixed voltage (BFV) to find the representative values of the MPP (de Carvalho et al. 2004). The control sets either the

operating point of the PV array to the BFV or the output voltage to the nominal load voltage. Operation is therefore never exactly at the MPP and different data has to be collected for different geographical regions. The PV array characteristic equation, which needs to be solved iteratively for the MPP, is manipulated to find an approximate symbolic solutions for the MPP in the algorithm proposed by Ritz-Rivera and Peng, (2004). This method, so-called linear reoriented coordinate method (LRCM), requires the measurement of V_{oc} and I_{sc} to find the solution. Other constants representing the PV array characteristic curve are also needed. The maximum error in using LRCM algorithm to approximate the MPP was found to be but 0.3%, but this was based only on simulation results, not on the experimental tests.

A new solar insolation estimator using the state vector machine (SVM) algorithm has been proposed by Ahmed and Al-Othman, (2010) for finding the MPPT of PV systems based on offline training. This estimation algorithm requires only measurements of PV voltage and power without the need for any environmental measurements. The offline training is achieved using the PV array output voltage and current as an input samples, the insolation as an output sample and consequently the maximum PV output power can be achieved. A relevant function between system inputs and output is deduced by offline training, and the insolation can be estimated directly online knowing the PV output voltage and current. The proposed estimation algorithm offers different advantage as good tracking efficiency, high accuracy, relatively high convergence speed and well control for the extracted power. Kim et al., (2006) proposed a new maximum power point tracker (MPPT) for a grid-connected photovoltaic system without solar array current sensor. The solar array current information is obtained, in this approach from the sliding-mode observer and fed into the MPPT to generate the reference voltage. The parameter values such as capacitances can be changed up to 50% from their nominal values, and the linear observer

cannot estimate the correct state values under the parameter variations and noisy environments. The structure of a sliding-mode observer is simple, but it shows the robust tracking property against modeling uncertainties and parameter variations. In this paper, the sliding-mode observer for the solar array current has been proposed to compensate for the parameter variations. The mathematical modeling and the experimental results verify the validity of the proposed method. The proposed system is possible to reduce the expensive current sensor and shows superior performance than the conventional system.

Faranda and Leva, (2008), Faranda et al., (2008), Berrera et al., (2009), Dolara et al., (2009), and Buyukdegirmenci et al., (2010) conducted extensive comparisons of the most used MPPT techniques among others. The Berrera et al., (2009) at Polytechnic of Milan, Italy, considering several irradiation conditions, performed extensive tests and experimental comparisons between some of the most used MPPT techniques. The aim of their work was to compare several widely adopted MPPT algorithms between them in order to understand which technique has the best performance. The evaluation of algorithms' performance was based on the power and the total energy produced by the panel during the same test cycle. In particular, different types of solar insolation characterized by low and medium irradiation level are considered, and the energy supplied by a complete PV array is evaluated. The different MPPT techniques have been implemented following the directions found in the literature. They found that one has been preferred or better improved respect to the others. The results show that the best MPPT technique is the modified P&O (P&Ob). The logic turned out to be effective in both the situations considered, providing always the highest efficiency. P&Ob technique shows its limit in the response to the irradiance variation at low irradiance level. The IncCond technique has an efficiency lower than the P&O techniques, but its response time is quite independent to the

irradiation values and its efficiency increase with the irradiance level. This technique can be a good alternative to the P&O methods in applications characterized by high, fast and continuous radiance variations, e.g. the PV applications in transportation. The two techniques are also equivalent concerning the costs and the software complexity. However, both the techniques require a microcontroller with medium to higher performances than the ones required by other techniques, due to the necessity of high computation capability. Other hill climbing techniques present acceptable results, and may provide good alternatives to the two previous techniques. In the present analysis, the CV, OV and SC techniques turned out to be the worst ones. Their performances are lower than the ones obtained with P&Ob techniques, especially in case of conditions very different from the radiance and temperature values. Moreover, OV and SC techniques require additional valves in the converter that decrease its efficiency and the output power. The CV technique is still a very simple one, which provides a very good efficiency for radiance values closed to 700 W/m^2 , with low costs. Hence, generally this technique can be selected only if there is the necessity to minimize the control system cost. However the cost of a microcontroller currently low, so that the implementation of the P&O type techniques is anyway preferred.

Feranda et al., (2008) and Dolara et al., (2009) presented a comparative study of ten widely-adopted MPPT algorithms, as well as their performance was evaluated using MATLAB/Simulink. In particular, this study compares the behaviors of each technique in presence of solar irradiation variations. Twelve different types of solar insulation were considered, in this study and the energy supplied by a complete PV array was calculated. Furthermore, regarding the MPPT implementation costs, a cost comparison was proposed taking into consideration the costs of sensors, microcontroller and additional power components. The MPPT implementation typology

greatly depends on the end-users' knowledge, with analogical circuit, SC, OV, or CV are good options, otherwise with digital circuit that require the use of microcontroller, P&O, IncCond, and temperature methods are easily to implement. Moreover it is important to underline that analogical implementations are generally cheaper than digital (the microcontroller and relative program are expensive). To make all the cost comparable between them, the computation cost comparison is formulated taking into account the present spread of MPPT methods. The number of sensors required to implement the MPPT technique also affects the final costs. Most of the time, it is easier and more reliable to measure voltage than current and the current sensors are usually more expensive and bulky. However, the irradiance or temperature sensors are very expensive and quite uncommon in applications and significantly may affect the cost of the MPPT controllers.

CONCLUSION

The chapter has covered the most common inverter and control topologies for PV systems, both grid-integrated and standalone configurations. The development of modern power electronics has been briefly discussed. PV cell characteristics and PV systems are also discussed including the new technology, inverters and their control methods. An important part of this chapter is dedicated to the study and simulation results of various MPPT topologies. Comparisons among some of the more diffused MPPT techniques in relation to their energy performance are also presented. The advantages and disadvantages of the most important MPPT algorithms are presented. The indirect methods ("quasi trackers") have the particular feature of not obtaining, but rather estimating, the maximum power for either irradiance or temperature. They must measure some of the PV generator's voltage and current PV (or both), the irradiance or use empirical data, by mathemati-

cal expressions of numerical approximations, to estimate the MPP from the specific PV generator installed in the system. Although, in many cases they can be simple and inexpensive, they are not very versatile with respect to load profile; none of them is able to obtain the MPP exactly, from PV in any atmospheric conditions. Subsequently, they are known as “quasi seeks”. On the other hand, the direct methods can be also distinguished (“true seeking methods”) which offer the following advantages: neither a large database nor a large memory is necessary for calculating the MPP; they are totally versatile with respect to the load profile; the seeking of MPP is independent of the variation of the parameters of the PV system. Likewise, the control circuit does not have to be fit for a specific generator, nor must it update when varying their parameters, and it is not necessary to know the level incident irradiance.

Nevertheless, in all direct methods up to now, the measurement of the voltage and current of PV generator are required. Notwithstanding, it has been shown that in the direct methods, it is possible to develop a strategy that allows obtaining the MPP by measuring only one variable, the current PV. Finally, it has been shown that other methods also exist, such as the artificial methods and the Fibonacci series based but two variables must be measured, at least. Also, we presented and discussed other methods that gained attention of the researchers, during last two decades, such as the artificial neural network methods, fuzzy logic based algorithms or other artificial intelligent approaches based in general on two variables measured. We also discussed the experimental results, classifications and comparisons, as well as the cost of various MPPT methods, algorithms and techniques. A comprehensive literature review and up-to-date references are also included.

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KEY TERMS AND DEFINITIONS

DC-DC Converter: A DC-DC Converter refers to an electronic circuit that allows for the conversion of direct electric current from one level of voltage to another level of voltage.

Fuzzy Logic Controller: A fuzzy logic controller (FLC) based on fuzzy logic theory provides a means of converting a linguistic control strategy based on expert knowledge into an automatic control strategy for various applications.

Maximum Power Point Tracking: Represents the automatic adjustment of the electrical load to achieve the greatest possible power harvest, during moment-to-moment variations of the light level (illumination), shading, temperature, and photovoltaic module characteristics.

MPPT Algorithm: Specialized control algorithms and techniques designed to operate a PV system at or near the maximum power point, in order to maximize the PV system power output.

Photovoltaic Array: When a number of solar or photovoltaic modules are installed together, this is commonly referred to as a solar array, or photovoltaic array. Arrays are a way to increase the potential of a solar electricity system, to provide a greater output of electricity.

Photovoltaic Module: A photovoltaic module is an interconnected collection of cells combined into one item. Solar modules allow for a wide range of varying sizes of solar panel products to be manufactured.

Photovoltaic System: A complete set of components for converting sunlight into electricity by the photovoltaic process, including the array and balance of system components.

Power Converter: A power converter is an electronic or electro-mechanical device for converting electrical energy. It may be converting AC to or from DC, or the voltage or frequency, or some combination of these.

PV Inverter: A PV inverter is a type of electrical inverter that is made to change the direct current (DC) electricity from a photovoltaic array into alternating current (AC) for use with home appliances and possibly a utility grid.

Solar Cell: A solar cell is any device that directly converts the energy in light into electrical energy through the process of photovoltaics.

Chapter 5

Photovoltaic Devices

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ABSTRACT

Photovoltaics (PV) have been the world's most rapidly growing energy source, with markets increasing at a compounded rate over the years. The electricity generating capacity of new photovoltaic product manufactured in 2006 exceeded new nuclear power capacity for the first time, with the gap widening in each year. The present continues to be a most exciting and challenging time for photovoltaics. More are recognising the possibility of a future where solar cells provide a significant part of the world's energy needs, without the environmental problems and escalating costs associated with the present mainstream approaches. Silicon is a semiconductor material which is mostly used for PV devices. Silicon is available in different forms like single crystal, poly crystalline, and amorphous. Most photovoltaic sales are of "first-generation" solar cells made from silicon wafers. First-generation PV research challenges are the cost reduction and further improving efficiency. The rapid growth of the photovoltaic industry is generating widespread interest in past and ongoing innovations of the PV technology. Silicon is quite brittle, so silicon wafers have to be reasonably thick, at least a fraction of a millimetre, to be sufficiently rugged for processing into solar cells with reasonable yields. Without this mechanical constraint, silicon would perform well even if very thin, over 100 times thinner than present wafers.

INTRODUCTION

Thin film or "second-generation" approach gives enormous potential cost savings. Not only are the costly processes involved in making wafers no longer required, but also there is an enormous

saving in silicon material and cells can be made more quickly over the entire area of large glass sheets. Thin films of some other poly-crystalline materials like Copper Indium Disengage, Cadmium Telluride, organic polymer materials, etc, are also used in the construction of photovoltaic

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cells. In large enough production volumes, even these reduced material costs will dominate thin-film costs. This has led to the interest in advanced “third-generation” thin-film solar cells such as all-silicon tandem solar cells, multi-junction solar cells, etc. targeting significant increases in energy-conversion efficiency. Higher conversion efficiency means more power from a given investment in materials, reducing overall power costs. The semiconductor bandgap can be controlled by quantum-confinement of carriers in small quantum-dots dispersed in an amorphous matrix of silicon oxide, nitride, and polymer materials. Cells based on “hot” carriers are also of great interest since they offer the potential for very high efficiency from simple device structures.

The development of a sustainable future energy option is one of the most important challenges facing the human race. The solar energy components of the energy needs will continue to grow in significance as pressures mount rapidly to generate power in a clean and renewable way. Photovoltaics (PV) clearly would be preferable to other options such as nuclear fission or fusion, or biomass – all with fundamental difficulties. The more widespread uptake of the technology would reduce greenhouse gas emissions from the burning of fossil fuels and, if sufficiently inexpensive, reduce the need for on-going investment coal-fired baseload electricity plant. For decades, PV devices have seemed the most promising technology to harvest the energy; however, despite gradual growth in use worldwide, PV devices still have not yet lived up to their potential for very high materials and processing cost. Globally research effort has driven towards the low-cost and high efficiency PV devices, resulting second and third generation PV devices. The main challenge with photovoltaics is to greatly reduce costs while improving device performance.

Photovoltaic is the process of converting sunlight directly into electricity using solar cells. Research and development of photovoltaics received its first major boost from the space

industry in the 1960s which required a power supply separate from “grid” power for satellite applications. Their application and advantage to the “remote” power supply area was quickly recognized and prompted the development of terrestrial photovoltaics industry. In the 1980s research into silicon solar cells paid off and solar cells began to increase their efficiency. In 1985 silicon solar cells achieved the milestone of 20% efficiency. The year 1997 saw a growth rate of 38% and today solar cells are recognized not only as a means for providing power and increased quality of life to those who do not have grid access, but they are also a means of significantly diminishing the impact of environmental damage caused by conventional electricity generation in advanced industrial countries.

The increasing market for, and profile of photovoltaics means that more applications than ever before are “photovoltaically powered”. These applications range from power stations of several megawatts to solar calculators. Specific materials generally semiconductors are commonly used in fabrication of photovoltaic cells. Silicon is a semiconductor material which is mostly used for this purpose. Silicon is available in different forms like single crystal, poly crystalline and amorphous. Thin films of some poly crystalline materials like Copper Indium Diselenide, Cadmium Telluride etc are also used in the construction of photovoltaic cells.

The present photovoltaic market is dominated by “first-generation” product based on silicon wafers, either single-crystalline or a lower-grade multicrystalline wafer (Figure 1). This market dominance is likely to continue for at least the next decade by silicon base PV technology. First generation production volume is growing rapidly with the technological emphasis upon streamlining manufacturing to reduce costs while, at the same time, improving the energy conversion efficiency of the product. Wafers are expensive and need quite careful encapsulation, since brittle and also thermally mismatched to the glass

coversheet, making first generation technology inherently material-intensive. To avoid associated cost penalties, several companies worldwide are commercialising “second-generation” thin-film cell technology based on depositing thin layers of the photoactive material onto supporting substrates or superstates, usually sheets of glass. Although materials other than silicon are of interest for these films, silicon avoids problems that can arise with these more complex compounds due to stability, manufacturability, moisture sensitivity, toxicity and resource availability issues. At the present time, such second-generation thin-films are entering the market in increasing quantities. More power from a given investment in material is possible by increasing energy-conversion efficiency. This leads to the notion of a third-generation of solar cell distinguished by the fact that it is both high-efficiency and thin-film.

The third-generation is specified as a thin-film technology, which has manufacturing costs per unit area similar to second-generation, but is based on operating principles that do not constrain efficiency to the same limits as conventional cells (31% for non-concentrated sunlight for these). Unconstrained thermodynamic limits for solar

conversion are much higher (74% for non-concentrated light, giving indication of the potential for improvement).

If a reasonable fraction of this potential can be realised, Figure 2 suggests that third-generation costs could be much lower than second-generation by a factor of 2 to 3. An “all-silicon” tandem cells based on bandgap-engineering using nanostructures was selected as the most promising. This involves the engineering of a new class of mixed-phase semiconductor material based on partly-ordered silicon quantum-dots in an insulating amorphous matrix. Photon up-conversion as a way of “supercharging” the performance of relatively standard cells forms a second line of research. A third is the investigation of schemes for implementing hot-carrier cells. Organic solar cells is the another area of PV technology for the low cost electricity generation.

CRYSTALLINE SOLAR CELLS (1ST GENERATION)

The University of New South Wales (UNSW) first developed the silicon solar cell of conver-

Figure 1. (a) Passivated emitter, rear locally diffused (PERL) crystalline silicon solar cell; (b) Multi-crystalline silicon solar cell (Annual report, UNSW, 2009).

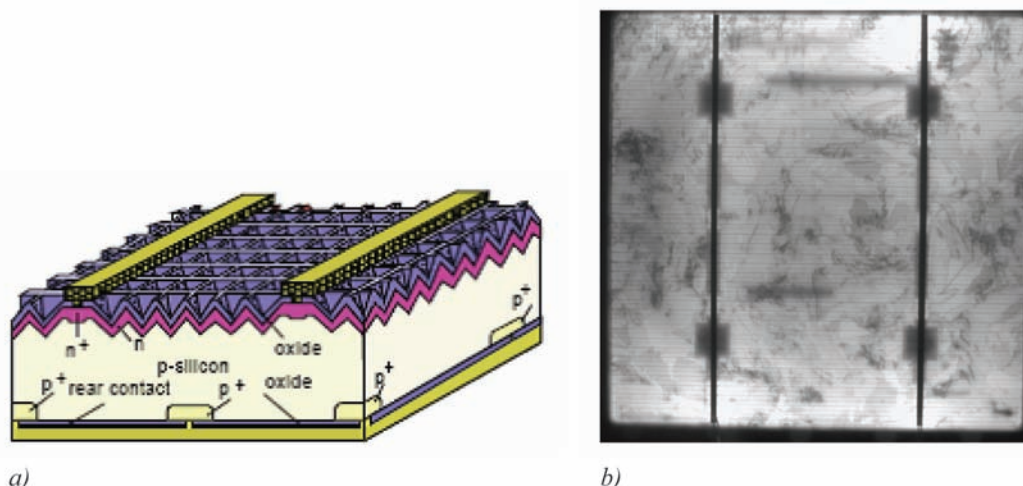
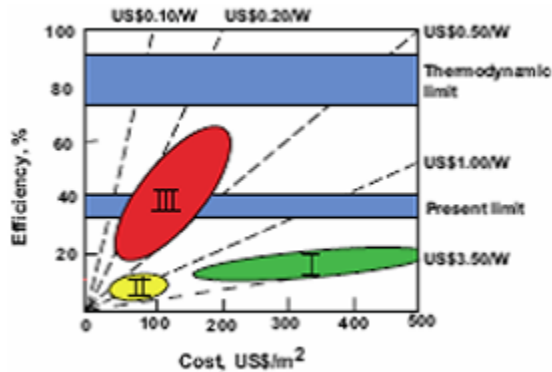


Figure 2. Efficiency and cost projections for first, second and third generation photovoltaic technology (wafers, thin-films and advanced thin-films, respectively) (Annual report, UNSW, 2009).



sion efficiency of 25% of incident sunlight into electricity in 2008. The passivated emitter, rear locally diffused (PERL) cell structure leading to this achievement is shown in Figure 1(a). The jump in performance leading to the attainment of the milestone resulted from more detailed knowledge about the composition of sunlight that led to the adoption of a new reference solar spectrum by the International Electrotechnical Commission in April 2008. The solar spectrum has more energy at both blue and red ends of the spectrum, with relatively less energy at intermediate green wavelengths. The exceptionally strong response of the PERL cell at both blue and red wavelengths increases its performance margin over less highly performing devices. This gives essentially 100% internal quantum efficiency (IQE) at blue wavelengths with impact ionisation increasing the IQE above 100% at wavelengths below 370 nm.

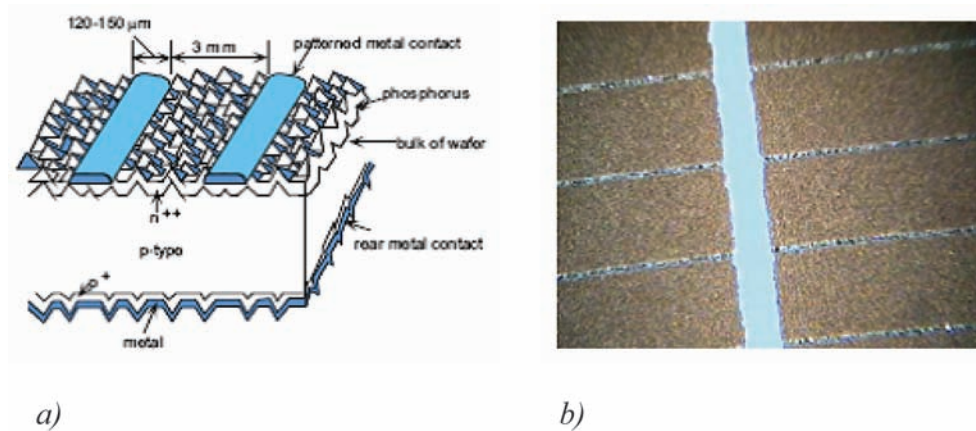
Screen Printed Solar Cells

The performance of the conventional screen-printed solar cell (as shown in Figure 3(a)) is limited for the last 30 years. The UNSW PV research groups have been identified its limitation and innovative approaches to redesigning the emitter and front

metal contact have been developed and analysed. In addition to overcoming the current and voltage limitations imposed by the design shown below, a further aim has been to retain compatibility with existing equipment and infrastructure currently used for the manufacture of screen-printed solar cells. Screen-printed solar cell technology dominates commercial photovoltaic manufacturing, with well over 50% share of markets. Despite the dominance of this technology, this solar cell design shown above has significant performance limitations that limit the cell efficiencies to well below those achievable in research laboratories around the world. In particular, the front surface screen-printed metallisation necessitates a heavily diffused emitter to achieve low contact resistance and also to achieve adequate lateral conductivity in the emitter since the metal lines need to be widely spaced compared to laboratory cells to avoid excessive shading losses. Such cells typically have emitters with sheet resistivities in the range of 40- 4 ohms.

Screen-printed fingers running perpendicular were developed to the heavily diffused grooves where electrical contact is made. A dielectric/AR coating passivates the top surface and isolates the metal from the lightly diffused top surface as shown in Figure 3(b). To raise this sheet resistivity to above 100 ohms per square as required for near unity internal quantum efficiencies for short wavelength light, serious resistive losses are introduced, both in the emitter and the contact resistance at the metal to n-type silicon interface. The conventional design of screen-printed solar cells has quite poor surface passivation in both the metallised and non-metallised regions. Even if good ohmic contacts could be made to more lightly doped emitters, the large metal/silicon interface area would significantly limit the voltages achievable due to the high levels of recombination in these regions and the corresponding contribution to the device dark saturation current. These voltage limitations are not of major sig-

Figure 3. (a) Standard screen-printed solar cell structure. (b) Screen-printed fingers running perpendicular to the heavily diffused grooves where electrical contact is made. A dielectric/AR coating passivates the top surface and isolates the metal from the lightly diffused top surface (Annual report, UNSW, 2009)



nificance at the moment due to the limitations imposed by the substrates. However, in the future if wafer thicknesses are reduced to improve the device economics, the cells will have the potential for improved open circuit voltages.

Laser Grooved Semiconductor Finger Solar Cells

The new emitter design developed in the UNSW is shown in Figure 3(b). The top surface is diffused to 100 ohms per square, while the heavily diffused grooves act as semiconductor fingers to carry the current to the screen printed silver fingers that run perpendicular to the grooves. Also not shown in the figure is the surface passivating dielectric that not only passivates the lightly diffused surface so as to give near unity internal quantum efficiencies for short wavelength light, but it also isolates the metal from these same regions to minimise the device dark saturation current. Importantly, the silicon is only exposed within the grooves, with the screen-printed metal having been shown to make excellent ohmic contact to the heavily phosphorus diffused silicon in these regions. Both thick oxides and silicon nitride layers, when

used with appropriate pastes, appear to provide adequate protection to the lightly diffused surface regions, preventing the screen printed metal from contacting the silicon. Fill factors above 79% have been demonstrated with this structure on large area devices of approximately 150 cm², verifying the effectiveness of this contacting scheme for minimising resistive losses. These cells also have near perfect response to short wavelength light as shown below, leading to short circuit current J_{sc} values of 36-37 mA/cm². Even though commercial p-type substrates are not capable of open circuit voltage (V_{oc}) above about 640 mV; the V_{oc} approaching this value has been achieved in commercial production with this technology, with corresponding efficiencies as high as 18.3%.

The grooves are typically spaced less than a millimetre apart so as to minimise resistive losses within the lightly diffused emitter, while the screen-printed metal lines can be spaced significantly further apart than in normal screen-printed cells due to the comparatively excellent lateral conductivity of the emitter achieved by the very heavy doping within the grooves. This concept of semiconductor fingers does not appear to have been used previously in commercial solar

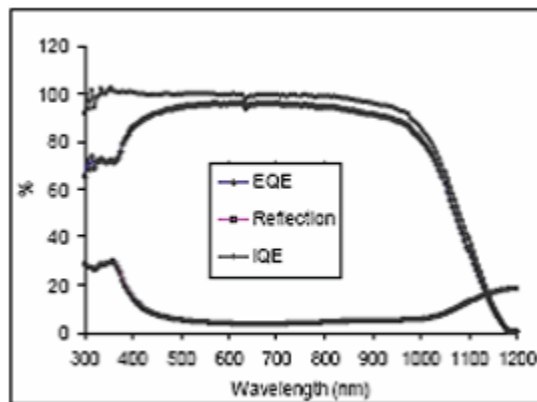
cells, and has considerable appeal as it facilitates good conductivity within the emitter, but without the normal trade-off found in screen printed cells. Normally, such regions of good emitter conduction are located at the top surface and therefore degrade the cell spectral response as shown in Figure 4 and current generating capability due to the corresponding extremely short minority carrier diffusion lengths in such regions.

A significant simplification of the proposed emitter design is applied a phosphorus doped passivating dielectric after lightly diffusing the top surface. The laser scribing conditions for groove formation are modified so as to melt the silicon rather than ablate it, thereby allowing large amounts of phosphorus to penetrate into the molten silicon, producing heavily doped channels rather than grooves as shown in Figure 5. This avoids the need for etching the grooves and subsequently diffusing the groove walls. An important benefit of this approach for multicrystalline silicon wafers is that the heavily doped regions are able to be formed without heating of the entire wafer. Some multicrystalline silicon wafers are known to degrade significantly if heated to temperatures above about 900 °C. The performance of these devices with CZ silicon however does not currently match that of the devices produced using the emitter design based on the use of laser grooving. A further enhancement in this technology would appear to be the incorporation of the laser chemical processing (LCP) techniques developed by the Fraunhofer Institute in Germany in conjunction with the laser company Synova. This would allow the superior performance of the laser grooved semiconductor finger solar cell to be combined with the simplicity and low cost of the laser doped semiconductor finger solar cell.

Advanced n-type Screen-Printed Solar Cells

Interest is increasing in n-type CZ silicon material to avoid the widely reported defects associated

Figure 4. Spectral response of semiconductor finger cell. External quantum efficiency (EQE), internal quantum efficiency (IQE) and light reflection are compared.

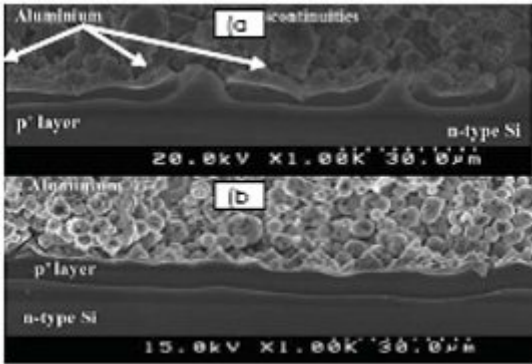


with the high boron and oxygen concentrations in p-type CZ silicon wafers. In particular, screen-printed Aluminium has been used as a simple and cost-effective way to create an Al-alloyed rear emitter for such n-type CZ material, especially in the n^+np^+ cell design with rear junction as shown in Figure 6.

Recently, the UNSW held the world record (jointly with Stanford University) for the most efficient n-type silicon devices with 22.7% conversion efficiency. The cell design was based on the inverted form of the PERL solar cell developed at UNSW and is shown in Figure 6. The cell design has been adapted to accommodate the use of low cost screen-printed solar cell processes involving the alignment of the screen-printed front metal lines to the heavily doped n^+ regions to form the equivalent of a selective emitter on the front surface and the use of a screen-printed aluminium grid pattern on the rear to form the localised p^+ regions during the spike firing of the Al.

The cells were fabricated using industrial sized (125x125 mm²) phosphorous-doped CZ n-type wafers of 3 ohm-cm resistivity and ~ 180 μ m thicknesses. A texturing process was performed in a NaOH/Isopropanol based solution to form random pyramids. A thin phosphorus diffused

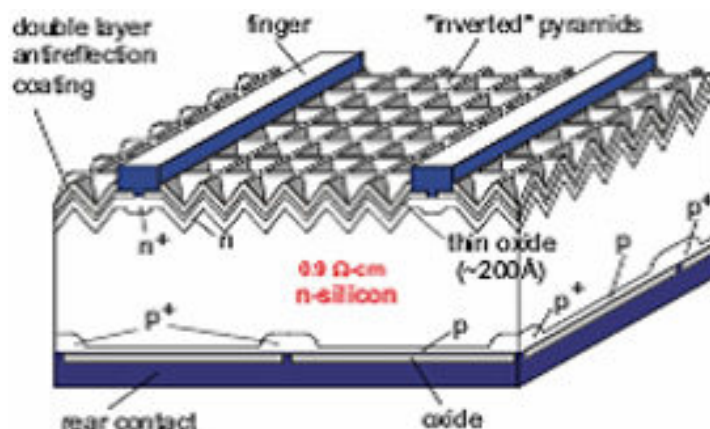
Figure 5. (a) top; (b) bottom. Cross-sectional SEM photos show: (a) discontinuities in the Al-doped p^+ layer; (b) a deep and uniform Al doped p^+ layer (Annual report, UNSW, 2009).



n^+ -layer with a sheet resistivity of 200 ohm/sq serving as the front surface field was created by a thermal diffusion at 850 °C using liquid POCl_3 source in a conventional tube furnace. A chemical etch containing HF and HNO_3 was then applied to the back of these wafers to remove the unwanted n^+ -layer from the surface. A silicon nitride layer with a refractive index of 2.05 and thickness of 75 nm was subsequently deposited using commercial Roth & Rau remote plasma PECVD system to simultaneously form an anti-reflective coating and provide passivation for the front surface as well

as the bulk material. After screen-printing with a selected aluminium paste on the entire back surface with a gap of around 2 mm from the edges, the wafers underwent an alloying process at 860 °C in a conventional conveyor belt furnace to produce the rear Al-alloyed emitter. A phosphorus dopant source was then spun onto the front surface, followed by the laser doping process using a 532 nm wavelength Q-switch diode laser to create locally heavily diffused lines. The wafers were rinsed and submerged in 1% HF solution for 30 sec to remove the dopant source and any native oxide from the laser doped lines. Lastly, light induced plating (LIP) was subsequently performed to deposit Ni, which was sintered at 400 °C, followed by Cu plating to form the front contacts. The performance improvement relative to the selective emitter screen printed counter parts arises primarily from the reduced shading losses by the top surface metalisation although slightly higher voltages (as high as 650 mV), fill-factors and yields are also achieved, apparently due primarily to the reduced metal/silicon interface area and superior alignment with the laser doped contacts. A spectral response measurement was performed to investigate different regions in the cell. A very high value of more than 95% was maintained for internal quantum efficiency (IQE) from 580 nm

Figure 6. Inverted form of the PERL (Passivated Emitter and Rear Locally diffused) solar cell developed at UNSW based on the use of n -type silicon (Annual report, UNSW, 2009)



to 960 nm. However, there was a slight drop in the short wavelength range, indicating that the front surface passivation can be further improved.

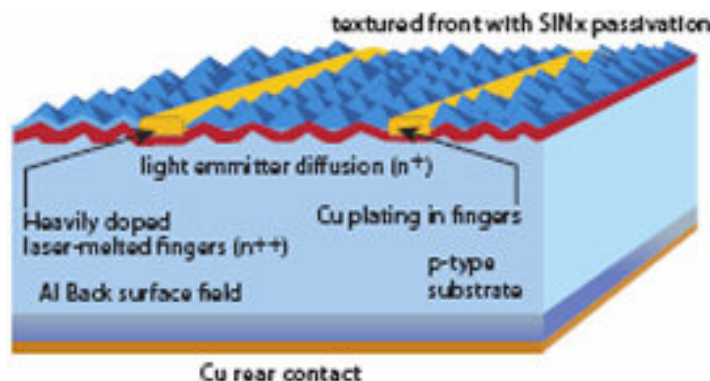
Laser Doped Selective Emitter Solar Cells

The benefits of a selective emitter have been well known and quantified for many years. The benefits of heavy doping beneath the metal contacts contribute significantly to the high performance levels achieved by technologies such as the Buried Contact Solar Cells, the semiconductor finger solar cell, the point contact solar cells and the world-record holding Passivated Emitter and Rear Locally diffused (PERL) solar cell. The heavy doping not only facilitates reduced contact resistance between the metal and the silicon, but probably more importantly it shields the high recombination velocity metal/silicon interface from the active regions of the cell. In addition, by restricting the heavily doped material to the immediate regions beneath the metal contact, little light absorption takes place in such regions thereby avoiding problems with carrier collection from heavily doped regions where the minority carrier diffusion lengths are very short. A potentially effective and simpler way of achieving a selective emitter is by using laser doping to produce the heavily doped

regions beneath the metal contacts as shown in Figure 7. Following top surface emitter phosphorus diffusion to about 100 ohms per square and silicon nitride deposition, an n-type dopant source is applied or can even be incorporated into the silicon nitride layer. A 532 nm NdYAG laser can be used to melt the silicon to a depth in the vicinity of a micron while simultaneously releasing the n-type dopants into the molten region. The molten silicon subsequently regrows epitaxially, heavily doped with phosphorus. Important processing parameters in the optimization of the laser doping process for textured surfaces have included laser pulse envelope shape, pulse duration, pulse frequency, laser light frequency, laser power, beam focus as well as the type of dielectric and dopant source being used.

The preferred implementation of the laser doping selective emitter technology also uses an equivalent laser doping/plating combination on the rear surface using a boron doping source. In this cell design, the majority of both the front and rear surfaces is well passivated using silicon nitride although the preferred rear surface passivation of the undiffused p-type surface uses somewhat different deposition parameters for best results. Implied V_{oc} values above 730 mV at one-sun demonstrate the near perfect passivation achieved with such surfaces. Following laser doping of the

Figure 7. Laser doped selective emitter solar cell with self-aligned plated metal contacts (Annual report, UNSW, 2009)



rear surface, even though plated contacts can be used similarly to on the front surface. The preferred rear contact can be achieved through depositing aluminium over the entire surface. The aluminium layer provides an excellent rear surface reflector. Even with standard commercial grade p-type CZ wafers, based on laboratory results it appears this technology will achieve comfortably over 20% efficiency on full sized commercial wafers when established in pilot production in early 2010 with impressive open-circuit voltages ~ 660 mV. This new technology, the laser doped selective emitter combined with light induced plating of the metal contacts are used by several manufacturers to replace the front surface screen-printed contacts. Two other popular implementations of the laser doping technology are the bifacial structure using laser doped self-aligned contacts of opposite polarity on both surfaces and the inter-digitated rear surface laser doped contacts for rear junction n-type devices.

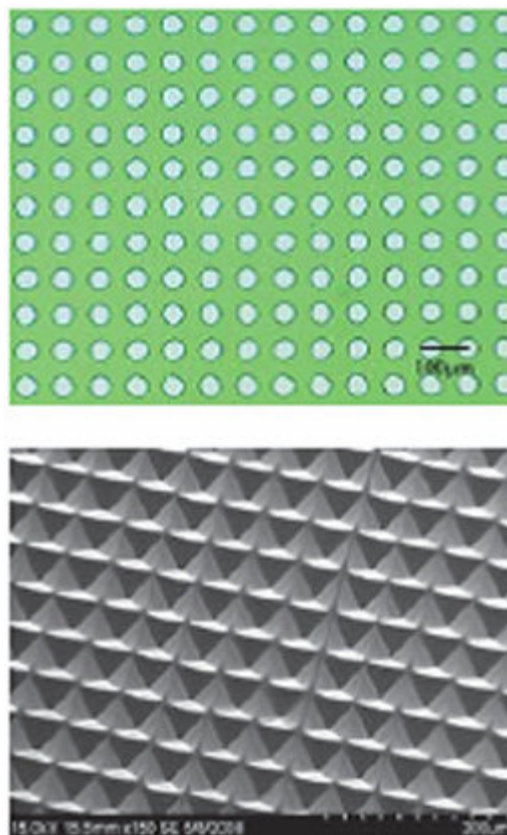
Inkjet Technology for Solar Cell Fabrication

Inkjet technology has been rapidly developing over the last decade, particularly for printing. In recent years, its application has been spreading to other fields, such as photovoltaics. CSG Solar first used this inkjet printing technology for their silicon thin film photovoltaic technology in 2006 for their commenced production for a corrosive material to etch patterns in a resist layer to facilitate metal contacting to the underlying silicon. The use of inkjet technology has been expanded to encompass a range of solar cell fabrication processes including texturing, grooving, patterning of dielectric layers for metal contacting, localized diffusions, etc. The techniques developed to carry out these processes are uniquely different to those used before. A non-corrosive plasticizer is inkjet printer onto a low cost resist layer, altering the chemical properties of the resist layer in these localized regions to make them permeable

to etchants such as hydrofluoric Acid (HF). This facilitates the patterning or etching of underlying dielectrics or semiconductor material to facilitate a range of semiconductor processes. A new method for patterned etching of SiO_2 and SiN_x dielectric layers has been developed and patented in the UNSW as shown in Figure 8.

The method uses Optomec's M3D aerosol jetting device to deposit a solution containing fluoride ions, according to an etching pattern, onto an acidic water-soluble polymer layer formed over the dielectric layer. The deposited solution reacts with the polymer layer, at the locations

Figure 8. Optical microscope photograph of ink jet patterned lines in a SiO_2 layer (top figure) and bottom: scanning electron microscope photograph of the grooves formed in the silicon surface following KOH etching of (top figure) (Annual report, UNSW, 2009)



where it is deposited, to form an etchant that etches the SiO_2 and SiN_x under the polymer layer to form a pattern of openings in the dielectric layer. After the pattern of openings is formed, the acidic water-soluble polymer and the etch residue are easily removed by rinsing in water. The method involves fewer steps than photolithography and is safer than existing immersion etching techniques in that the corrosive etchant HF is only formed in-situ on the surface to be etched. Furthermore, the method uses small amounts of inexpensive chemicals and produces significantly less hazardous fluoride waste than existing immersion etching methods. Aerosol jet printing is a new deposition technology being pioneered by Optomec, Inc. The technique enables the finely-controlled deposition of an aerosol, which is generated from a liquid, by using a sheath gas to constrict the aerosol into a fine jet which is directed to the substrate. The technique has been previously used in applications such as printed electronics, fuel cells and displays. The aerosol etching method has been used to etch groove structures in SiO_2 which have been thermally grown on polished silicon wafers. By varying the aerosol and sheath gas flow rates the ge-

ometry and depth of etching can be varied. A particular exciting application of this inkjet technology work is for very high efficiency silicon solar cells. The key to high-efficiency silicon solar cells is the ability to form small-area metal contacts to the silicon through dielectric passivating layers.

THIN FILM SOLAR CELLS (2ND GENERATION)

Organic Solar Cells

Interest in organic photovoltaic (OPV) with increasing conversion efficiency has grown exponentially over recent years as shown in Figure 9. The key development in the OPV device is the bulk hetero-junction cell obtained by blending donor and acceptor layers, a device structure well suited to the associated short excitonic diffusion lengths. The fullerene based acceptor material (PCBM) is interspersed with a donor polymer, commonly P3HT, with line-bond diagrams for these materials shown in Figure 10(b). The workhorse for OPV research has become polymer-fullerene bulk het-

Figure 9. Recent improvements in independently confirmed efficiency for small area ($\leq 1\text{cm}^2$) organic solar cells (extracted from Green et al. 2006 -2009)

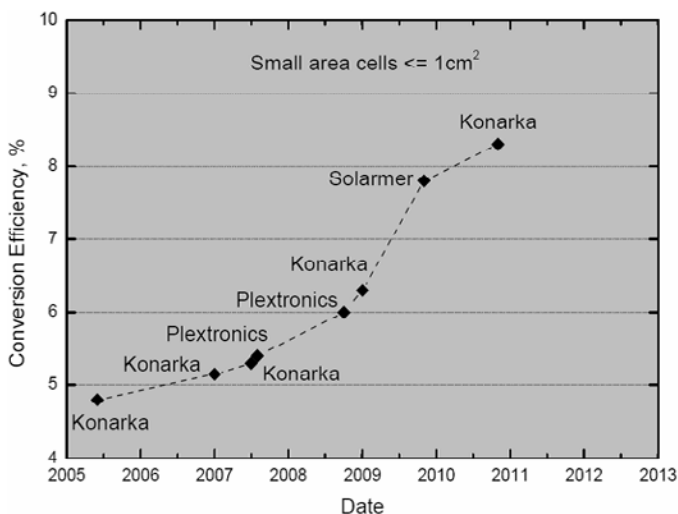
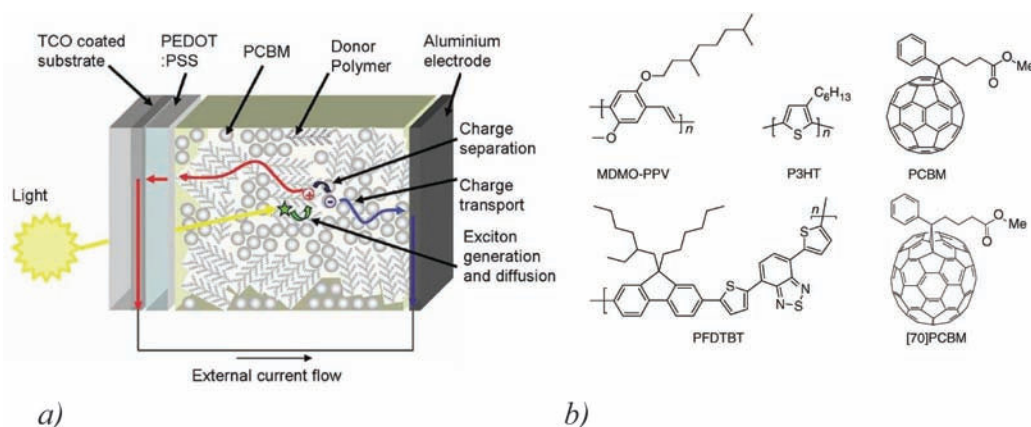


Figure 10. (a) Typical bulk-heterojunction organic cell structure used to produce the results of Figure 9; (b) Common donor and acceptor materials for polymer-fullerene heterojunction solar cells. Donors: MDMO-PPV _ poly(2-methoxy-5-(3,7-dimethyloctyloxy)-p-phenylene vinylene); P3HT _ poly(3-hexylthiophene); PFDTBT _ poly(2,7-(9-(2-ethylhexyl)-9-hexylfluorene)-alt-5,5-(4,7-di-2-thienyl-2,11,3-benzothiadiazole)). Acceptors: PCBM _ 3-phenyl-3'-H-cyclopropa fullerene-C60-Ih-3-butanoic acid methyl ester; (70)PCBM: 3-phenyl-3'-H-cyclopropa(8,25)(5,6)fullerene-C70-D5h(6)-3-butanoic acid methyl ester (Brabec et al., MRS Bulletin, July 2008, p.71; <http://www.solarmer.com>; Basore, 2006, Proc. 21 st European PV Solar Energy Conf., p544).



eroheterojunction devices fabricated by coating a thin layer of PEDOT:PSS on the top of cleaned ITO substrates followed by a blend of PCBM/P3HT (or other donor polymer), then by vacuum evaporation of Al and annealing as shown in Figure 10(a). Both packaging and cell efficiency had improved by 2006 to the stage where independent measurement of cell efficiency was both feasible and warranted, with subsequent efficiency improvements well documented. Using the above structure, Konarka, USA established 4.8% efficiency for a tiny 0.14 cm² cell in July 2005. Konarka increased this to 5.15% in December 2006 with 5.24% posted for a 0.7 cm² cell in July 2007. Companies such as Plextronics have reported roughly comparable results using similar materials with 5.4% efficiency confirmed in July 2007 for a 0.1 cm² device, 6.0% in August 2008 for an even smaller 0.04 cm² cell and 2.0% as recently as 28 January 2009 for a 224 cm² module. OPV device developer Solarmer Energy achieved 7.9% efficiency in December 2009. In November 2010, Konarka achieved their

highest OPV efficiency 8.3%. The history of OPV conversion efficiency is shown for small area (≤ 1 cm²) cells in Figure 9.

The nanoscale texture or thin film morphology of the donor/acceptor blends used in most OPV devices is a critical variable that can dominate both the performance of new materials being optimized in the lab and efforts to move from laboratory-scale to factory-scale production. Although OPV conversion efficiencies (up to 8%) cells have improved significantly in recent years, progress in morphology optimization still occurs largely by trial and error, in part because much of our basic understanding of how nanoscale morphology affects the optoelectronic properties of these heterogeneous organic semiconductor films has to be inferred indirectly from macroscopic measurements. The morphology of the active film is a very important factor to produce high efficiency devices. Films spin-coated from blend solutions undergo separation of the donor/acceptor phases. The scale of the phase separation

depends on the solvent, solubility of the materials and parameters of the spin-coating process such as speed, temperature, etc. If the morphology could be controlled on a molecular scale the efficiency of charge separation and transport could be expected to be substantially higher.

OPV Challenges

Plastic solar cells rolled out like cling-wrap readily capture the imagination of the public, politicians and even venture capitalists. However, although there may be a near-term role in specialised consumer products, viable photovoltaic products able to compete with inorganic solar cells within mainstream markets are a long way from being a reality. Many new ideas and much new technology will be required before competitive products eventuate. The attraction of OPV is the low costs that may be possible due to high throughput manufacturing on large flexible plastic sheets, rather than on the thick glass substrates favoured by the inorganic cell technologies. However, there are three main challenges to making this type of technology a reality:

- Low conversion efficiency of present OPV cells
- Poor stability and durability
- Present expense of some OPV materials.

Energy conversion efficiency (ECE) has improved steadily over recent years as shown for the independently confirmed results of Figure 9. If the present rate of progress can be maintained, it may be possible to improve the recent 8.3% efficiency record (December 2010) to 10% efficiency within one/two years. It should be noted, however, that the results shown are not for large area sheets but for tiny test devices only 1 cm² or smaller in area.

A multi-pronged approach is needed involving fundamental investigation of new polymeric material options for improved efficiency/stability by computer simulation, synthesis of new materi-

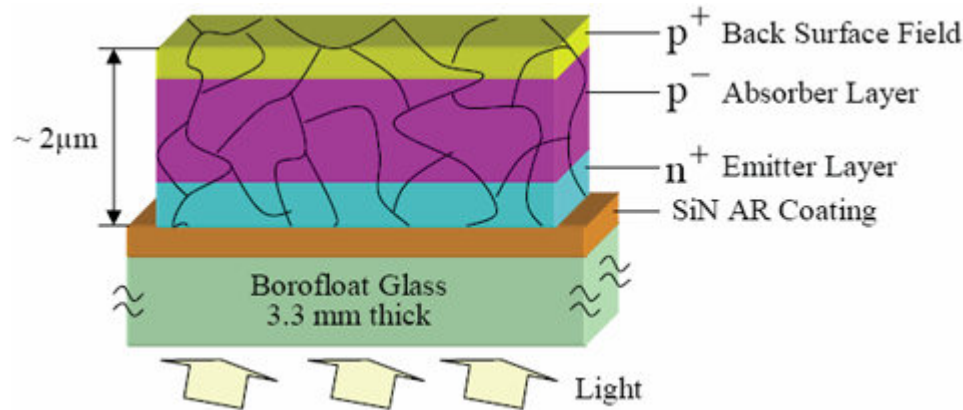
als as required, experimental cell fabrication, cell performance characterisation and modelling, cell design improvement, implementation of a range of new ideas relevant to recombination reduction and improved light trapping in cells and exploration of the potential of a range of “third generation” options as a means of significantly boosting performance. While retaining the advantages of OPV, the hybrid approach offers additional advantages including the potential for higher conversion efficiency and improved stability. The approach also allows control of bandgap in a stable material system. This opens the opportunity for fabricating optimised tandem stacks of OPV-based cells, with much higher efficiency potential than 10%. Many new ideas and much new technology will be required before competitive products eventuate.

The OPV cell needs to be protected from oxygen and water vapour to increase the stability and durability, which is difficult to achieve using permeable organic material. Barrier coatings containing multiple thin blocking layers of optically transparent inorganic material are the most promising option. It is also very important to identify the key degradation mechanisms to improve the device lifetime and performance. Much work needs to be done, both in cell material selection and in low cost encapsulation, before a level of durability required for mainstream product is obtained. Finally, even though the low cost of OPV is stressed by proponents, the fullerene-based materials used in all the cells reported are very expensive to synthesise at present. It is expected that fullerene costs will reduce greatly as production volumes increase.

Polycrystalline Thin Film Solar Cells

Thin-film poly-Si solar cells technology on glass substrate as shown in Figure 11 is developing rapidly and it is expected to lead to significant cost reductions of PV electricity. The best developed poly-Si solar cells technology is on glass substrate. The CSG Solar has developed the best solar

Figure 11. Schematic structure of a p-type poly-Si solar cell on a planar glass (layer thicknesses and grain size not to scale) (Annual report, UNSW, 2009)

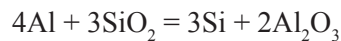


cells by an approximately $1.5\ \mu\text{m}$ thick PECVD-deposited amorphous silicon (a-Si) precursor diode, crystalline at about 600°C using solid-phase crystallisation (SPC). The highest achieved conversion efficiency of minimodules produced by the CSG technology was 10.4% (Keevers, et al., 2007). The UNSW group is exploring a range of alternative and advanced poly-Si on glass processes and approaches. The group R&D work over the past years has led to innovative solutions for the key steps of the solar module fabrication process, including glass texturing and light trapping, silicon deposition, grain size improvement, and solar cell metallisation and interconnection. The glass texture is prepared by chemical reactions between the glass and a sacrificial Al film (“aluminium-induced texture”, AIT (Widenborg, et al., 2004). The antireflection and barrier layer was a PECVD or reactively sputtered silicon nitride (SiN) film. Silicon films on SiN are deposited by either PECVD (industry standard, but low deposition rate) or electron beam evaporation (e-beam, high deposition rate). As-deposited Si films are crystallised by rapid thermal annealing (RTA) at $900\text{--}1000^\circ\text{C}$ and hydrogenation at about 600°C . To obtain a larger grain size, some of the cell structures under development are formed by

solid phase epitaxy (SPE) on a poly-Si seed layer prepared by Al induced crystallisation (AIC).

Glass Texturing

A unique glass texturing process is developed at the UNSW and it is referred to as “aluminium induced texture” (AIT). A thin sacrificial Al film is deposited by evaporation or sputtering on planar glass, followed by annealing at intermediate temperatures ($\sim 600^\circ\text{C}$) in an inert gas atmosphere. The anneal initiates a red-ox reaction of aluminium and Al is oxidised to Al_2O_3 and SiO_2 from the glass is reduced to silicon, as follows:



A surface texture is imparted to the glass according to the nucleation conditions provided during this anneal. Wet-chemical etching removes the reaction products from the glass surface and reveals the glass texture. Preferred Al deposition method is in-line DC Al sputtering, but both thermal and e-beam Al evaporation has been shown to work very well. A typical atomic force microscope (AFM) image of the bare AIT glass surface with the RMS roughness of 800 nm and

Figure 12. (a) AFM image of bare AIT glass surface and (b) SEM images image of 2 μm thick poly-Si film on AIT glass

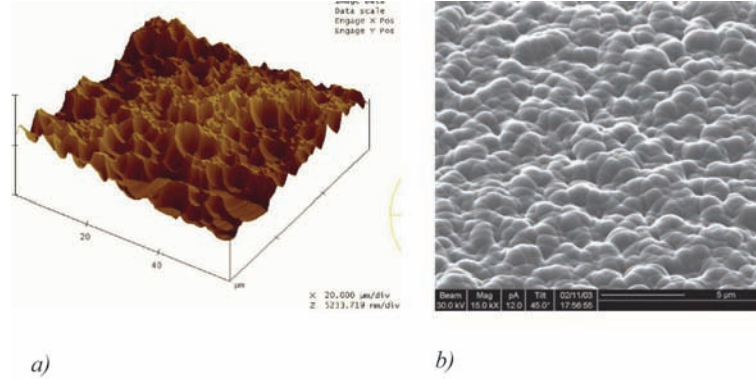
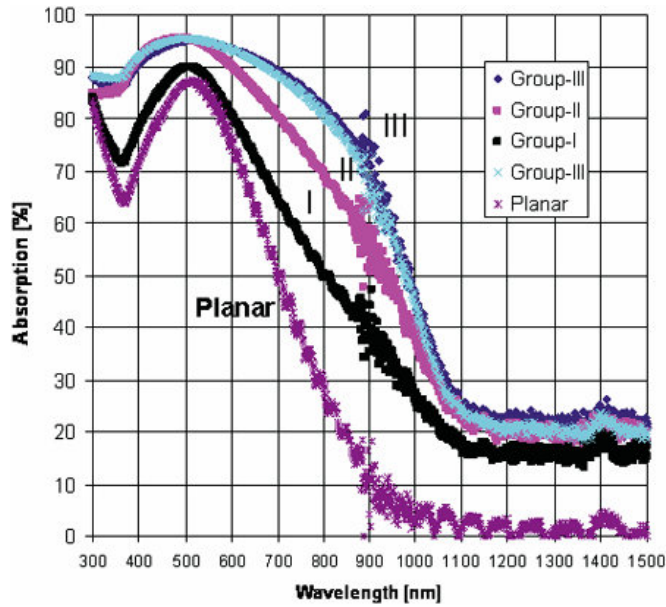


Figure 13. Measured optical absorption data for 2.7 μm thick SPC poly-Si thin film solar cells on planar and different etched AIT glass fabricated by evaporation with air as the back surface reflector (BSR)



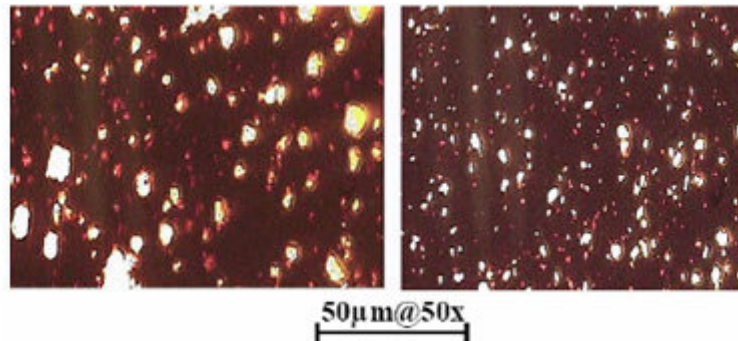
an SEM image of the AIT glass coated with a 2 μm thick poly-Si film are shown in Figure 12.

To examine the light trapping effect of different textures, 2.7 μm thick poly-Si thin films were fabricated on these AIT glass samples by PECVD of a-Si:H films followed by SPC, rapid thermal annealing, and hydrogenation. The optical properties of the poly-Si films on the AIT glass were

characterised by optical absorption based on reflectance(R) and transmittance (T) measurements as shown in Figure 13.

When the AIT glass is prepared with evaporated Al and by HF: HNO_3 etching, the poly-Si films have the highest optical absorption (Group-III) while those prepared by KMnO_4 :HF etching (Group-I) have the lowest absorption as shown

Figure 14. Optical microscope transmission images of EVA (right) and PLASMA (left) films after annealing for 7 hours



in Figure 13. It is also found that the optical absorption in the poly-Si films is closely correlated with the number of bright sidewalls of the textured features observed for the uncoated AIT glass in the optical microscope reflection dark field mode images. The higher number of bright sidewalls, the higher the optical absorption. The absorption in the 2.7 μm thick poly-Si films on the best AIT glass in the 500–1000 nm wavelength interval is very close to the calculated random scattering absorption limit, based on Monte Carlo ray tracing. It should be noted that the significantly higher absorption than the theoretical limit at 1000 nm and above can be explained by the enhanced parasitic absorption in the glass and/or measurements errors as discussed elsewhere (Goldschmidt, et al., 2003). The poly-Si films on the AIT glass fabricated by using in-line Al sputtering have optical absorption similar to that of the films on the AIT glass fabricated by using the thermally evaporated Al proving the scalability of the AIT process. The results show that AIT glass has a great potential for thin-film poly-Si solar cells.

Comparative Solid Phase Crystallisation (SPC) of Evaporated (EVA) and Plasma Si Films

SPC of a-Si films is one of crucial processes in the poly-Si thin-film solar cell fabrication. It has

been developed for and traditionally applied to hydrogenated a-Si films deposited by PECVD. The evaporated films are also crystallised using the same SPC process. However, the evaporated films differ from the PECVD films in both the composition and the morphology. It can be expected they crystallise differently, and for the optimum solar cell performance they may require SPC conditions different from those for the PECVD films. The EVA and PLASMA samples had similar $n^+p^-p^+$ diode structures, except the different p^- absorber layer thickness, 1.8 μm and 1.2 μm , respectively. Images from the optical transmission microscopy at the intermediate SPC stages from 7 hours show more advanced crystallisation in the EVA films, which have fewer and larger grains than the PECVD films as shown in Figure 14.

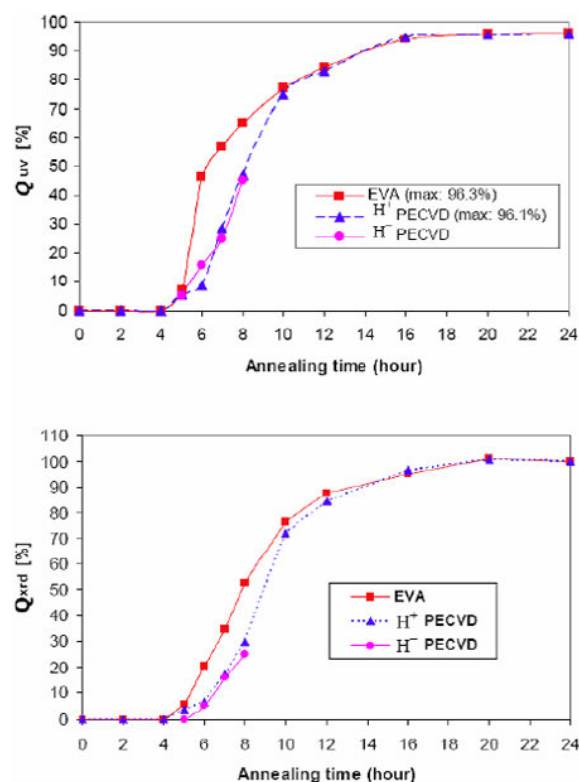
The Normalised Crystal Quality factor calculated from the sample UV-reflectance and XRD spectra increases more rapidly for the EVA films compared to the PECVD films for times between 5 and 10 hours, and then it develops similarly for both film types as shown in Figure 15. Q_{UV} , which compares the crystallinity between the films and c-Si wafer, reaches 96% for all poly-Si films. All characterisation methods indicate that the crystal growth starts after about 4 hours at 600°C, perhaps, marginally earlier in the EVA films. The intermediate stage, where the crystallisation degree quickly increases from 5% to 70%, has a higher

rate in the EVA films than in both hydrogenated and dehydrogenated PECVD films. Moreover, taking into account that EVA samples were actually $0.6\text{ }\mu\text{m}$ thicker than PLASMA samples, the observed differences in the SPC are expected to be even more evident for the samples of the same thicknesses. About the same onset of the crystallisation points at similar incubation and nucleation times/rates occurred in all films regardless of the presence of hydrogen. The optical transmission images show evidence of a more sparse nucleation in the EVA films. However, all methods agree that those sparse nuclei are more active and develop into faster growing grains. Thus the resulting quality of EVA poly-Si diodes should be at least as good as for the PECVD poly-Si films, which have demonstrated the cell efficiency of 10.4% (Keevers, et al., 2007). The faster crystal growth in the evaporated films potentially allows a shorter SPC process for poly-Si thin-film cell fabrication.

CdS/CdTe Solar Cells

Early 1950's, cadmium telluride has been known as a good candidate for solar cells when it could be doped n- and p-type and its band gap energy at 1.45 eV is close to optimal for solar energy conversion (Jenny, et al., 1954). In 1991 Ting L. Chu reached CdS/CdTe solar cell 15% efficiency (Chu et al, 1991, 1992 and Aramoto, et al., 1997). This opened the potential for significant commercial interest by a dozen new start-up companies. The maximum solar conversion efficiency of the CdS/CdTe cell that was already achieved in 2001 now stands, as confirmed by NREL at 16.5% (Ban et al., 2006). First Solar in 2005 was achieved to reach a production capacity of 25 MW/year. The CdS/CdTe cell became the preferred commercial solar cell because of the ease of reproducible fabrication of large area cells, and their better long-term stability. The production of a large area of these solar cells by relatively simple vacuum

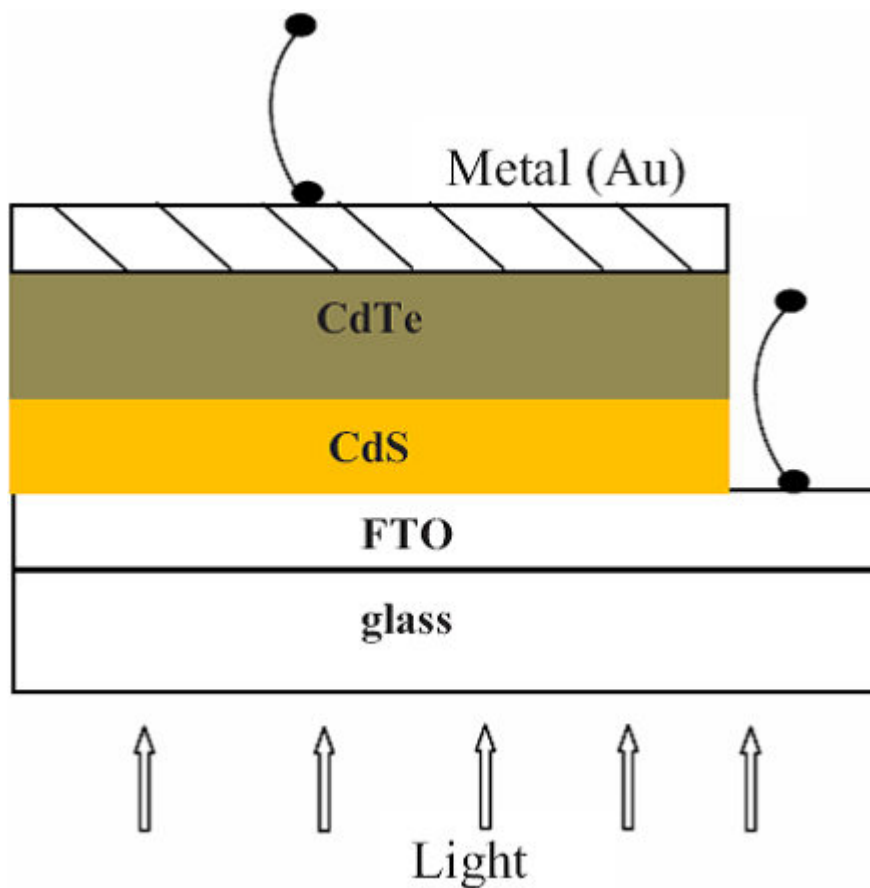
Figure 15. Evolution of normalised crystal quality factors from UV (above) and XRD (below) during annealing of EVA and hydrogenated (H^+) and dehydrogenated (H^-) PLASMA Si films.



deposition has led to a further rapid development of a thin-film solar cell industry.

The CdS/CdTe solar cell is produced by evaporation of a thin CdS layer on top of a conductive glass substrate, followed by another evaporation of a typically $2\text{ }\mu\text{m}$ thick CdTe layer and the deposition of a metal contact layer to complete the initial process as shown in Figure 16. The cell is then treated for a short time at a temperature of about $450\text{ }^{\circ}\text{C}$, usually with a CdCl_2 flux that causes a partial crystallization of the two semiconductors as shown in Figure 17. This allows for the copper doping of the CdS in the same process (the flux or other components at the outer interface of the CdTe layer provides the source for this doping) (Hegedus, et al., 2005). All of these procedures can be performed economically on a semiautomatic

Figure 16. A schematic diagram of the basic structure of the glass/FTO/CdS/CdTe/metal thin-film solar cell. The fluorinedoped tin oxide (FTO) coated glass substrate are commercially available.



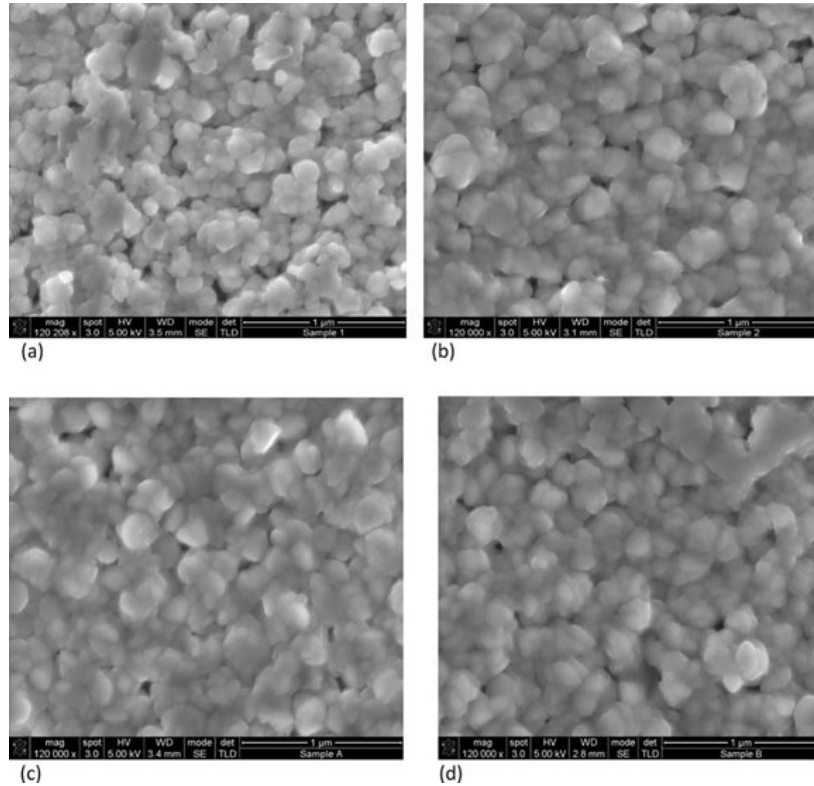
production line. In the last two decades numerous other compounds were investigated in an attempt to replace CdS and achieve similar conversion efficiency improvements, or even surpass the efficiency of CdS. All these attempts failed and only a few materials showed some, but insignificant, improvements of the CdTe or CIS type solar cells (Ferekides, et al., 2000).

The reason why CdS is a good partner to CdTe was first thought to be the enhanced optical transmission through the covering CdS layer, that is caused by the lower index of refraction of CdS compared to CdTe and experiences a lower light reflection from the cell surface. This effect improves the cell current and the substantial increase of the open circuit voltage and the fill factor in

the current–voltage characteristics. The conversion efficiency enhancement by a thin layer of CdS was known for almost three decades, but an explanation of the reasons for it was elusive. Only recently, a more thorough analysis of the physical behaviour of copper-doped CdS has helped to clear up this puzzle (Böer, 2009, 2010).

It is known that CdS is an n-type semiconductor that, when doped with copper becomes highly photoconductive. Under optical excitation of solar cell, the electron density is found in the order of 10^{18} cm^{-3} . Such photoconductivity can easily be quenched by additional low energy excitation, such as by infrared light, or, what becomes important in the case of the solar cell, by an intermediate electric field. This field causes a Frenkel-Poole

Figure 17. SEM pictures of ((a) and (c)) as-deposited, (b) heat-treated (400°C for 20 min in air), and (d) CdCl₂-treated followed by heat-treated ED-CdS layers

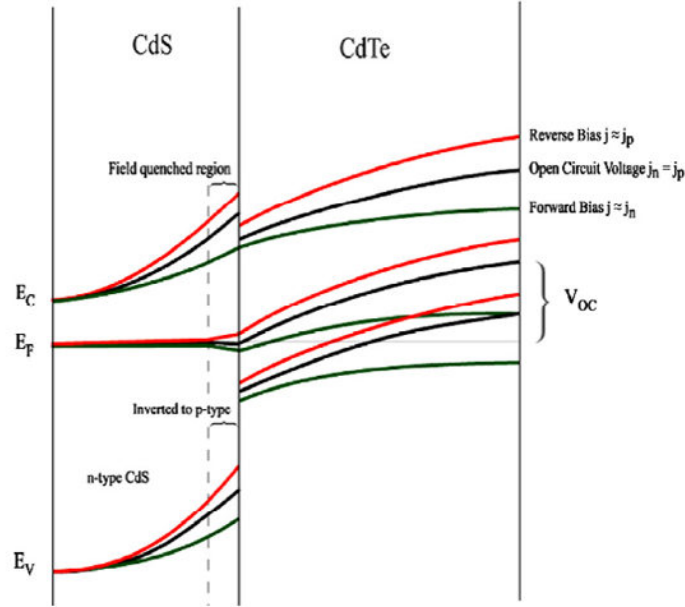


excitation (Böer et al., 1970) of trapped holes from Coulomb attractive hole centers into the valence band. The now set-free holes can be trapped by fast recombination centers from which they can interact with the conduction electrons, permitting enhanced recombination/and thereby reducing their density. These intermediate electric fields can be reached at the CdS side of the junction to the CdTe, causing, in the corresponding thin CdS layer, such “field quenching” to occur (Hadley, et al., 1972). The field quenching is one of the reasons for the cell improvement since it can reduce the electron density at the junction interface and hence its back-diffusion into the CdTe, that would represent a junction leakage. Such a leakage consequently would result in lower solar conversion efficiency, as it is observed in the uncoated CdTe cells.

One can now include several other important factors to explain the behavior more quantitatively.

1. The electric field at the CdS side of the junction is a function of the voltage drop that is observed at various points of the current–voltage characteristics: It is generally low in forward bias and increases rapidly when approaching the open circuit voltage, and beyond in reverse bias. This means, for sufficient forward bias, there is no field quenching, and hence electrons can travel through the junction easily. However, as the field increases when V_{oc} is approached, field quenching sets-in and substantially reduces such electron leakage (Böer, 2010).
2. CdS in the quenched region shows a negative differential conductivity, that is, the

Figure 18. Schematic energy band diagram of CdS/CdTe solar cell. E_C , E_F and E_V are the conduction band, Fermi energy level and valence band energy levels, respectively



- photocurrent decreases with increasing applied voltage. When the field quenching is strong enough, a high-field domain is created in which the field is limited to ~ 50 kV/cm. This field is approximately the same as that in which substantial field quenching is observed. In fact, the field quenching is the cause of the negative differential conductivity that is necessary to initiate the high-field domain (Böer, et al., 1968). This maximum field near the CdS/CdTe interface is too low to permit electron tunneling through the junction, which otherwise would shunt the junction and reduce the solar cell efficiency.
3. The field quenching near the CdS/CdTe interface can be strong enough to turn the CdS into a p-type layer (Böer, et al. 1967). This causes the Fermi level in this layer to move much closer to the valence band. Since the Fermi level at open circuit condition must remain horizontal, this means that both the valence and conduction bands curve up in the field quenched region and the conduction band at the interface must disconnect from the conduction band of the CdTe, to which it was connected in forward bias (Böer, 2010). This again limits the electron back-diffusion into the CdTe.
 4. To permit such relative shift of the bands between CdS and CdTe, a change of the dipole moment at the interface, which determines the band connection (or the band offset), is required. There is experimental evidence that in copper-doped CdS platelets, the dipole moment that is involved in a Schottky barrier to a metal electrode can be changed by changing the photoconductivity (Böer et al., 1969, 1971). That seems to justify the assumption that such a change of the dipole moment at an even 'softer' interface can occur.
- With these conditions, one can draw the band diagram of a CdS/CdTe solar cell close to the junction interface (Hadley, et al., 1972) as it is shown in Figure 18. By interpretation of this figure, one

should recognize that the influence of the outer electrodes is omitted, and so is any additional junction recombination. This is a qualitative drawing that also does not show the quasi-Fermi levels that need to be considered but for which additional information on the defect structure on both sides of the junction is required. The model picture should therefore only be considered to point attention to the involved basic physics and is no attempt to quantitatively model an actual CdS/CdTe solar cell. Field quenching is quite sensitive to the distance between the Coulomb attractive centers that are produced by copper doping (Hadley, et al., 1972). If this density is too low, then the quenching is not efficient enough to reduce the electron density markedly. If, on the other hand, the density is too high, then these centers become too close and the critical field for Frenkel-Poole excitation becomes much higher. Accidentally, the saturation level of copper in CdS is about 100 ppm, which brings the distance between the copper atoms to its optimal value (Böer, et al., 1970). Though in some other semiconductors one can induce such field quenching and consequently negative differential conductivity, one must design the doping just to the right level. This is too complicated to achieve over large enough areas, causing this alternative layer to become highly inhomogeneous and its beneficial effect limited to a small percentage of the solar cell area.

Thin film CdTe solar cells are typically heterojunctions with CdS being the n-type partner, or window layer. Efficiencies as high as 16.5% have been achieved, but still there is some potential for increasing them. We make an analysis of the typical CdS/CdTe superstrate solar cell, and from it we establish critical issues and different lines of research in order to improve the current efficiencies.

THIRD GENERATION SOLAR CELLS

Multi-Junction Tandem Solar Cells

III–V semiconductor materials multi-junction (MJ) solar cells have the potential to achieve conversion efficiencies of over 50% (Yamaguchi, 2003) and are promising for space and terrestrial applications. In order to apply the III–V compound semiconductor solar cells widely, their cost reduction by using thin-film structures fabricated on inexpensive substrates such as silicon (Si) and their concentrator operation is necessary. Thin-film MJ solar cells on Si substrates have a great potential for high-efficiency, low-cost, lightweight and large-area space cells. There are, however, major problems such as high-density dislocation generation and residual stress in III–V compound films grown on Si substrates, owing to large lattice mismatch and large thermal expansion coefficient differences between III–V compounds and silicon. These problems have prevented solar-cell property improvement. Especially, the density of dislocations short the minority-carrier lifetime in III–V-on-Si. Some authors have developed high-efficiency GaAs-on-Si cells (Kadota, et al., 1989) as a result of dislocation density reduction in GaAs films on Si substrates by introducing novel structures such as AlGaAs/GaAs super lattice (SL) and InGaAs/GaAs strained layer super lattice (SLS) in addition to thermal cycle annealing (TCA).

The most obvious III-V materials for direct epitaxial III-V integration on Si is gallium phosphide (GaP) because of the small lattice mismatch to Si, 0.37% at 300 K. Early research into interfacial defect mitigation in GaP/Si heteroepitaxial integration focused on high-indexed Si substrates. First researcher has started their researches on AlGaAs/GaAs 2-junction solar cells since 1982 and same group has demonstrated 20.2% efficiency by proposing double hetero (DH) structure tunnel junction as a sub cell interconnection in 1987 (Yamaguchi, et al., 1987). In Japan, based on such an activity, R&D project for “Super-high Effi-

ciency MJ Solar Cells” has been conducted under support by NEDO since 1990 (Yamaguchi et al., 1996, 1997) as a long-term target to the early 21st century, in which challenges and efforts are made in the development of super-high-efficiency solar cell technology, aiming at a dramatic increase in conversion efficiency of over 40% and developing innovation technologies. The mechanically stacked InGaP/GaAs/InGaAs 3-junction cells (1 cm^2) have reached the highest (1-sun world-record) efficiency of 33.3% at 1-sun AM1.5G by joint work of Japan Energy Co., Sumitomo Electric Co. and Toyota Tech. Inst. in 1997 (Yamaguchi et al., 1996, 1997). In 2004, the world-record MJ efficiency concentrator was InGaP/InGaAs/Ge 3-junction solar cells with an efficiency of 37.4% at 200-suns AM1.5 and out-door efficiency of 27% with area of 7000 cm^2 as a result of widening top cell band gap, current matching of sub cells, precise lattice matching of sub cell materials (Yamaguchi, et al., 2006).

Multiple stacking of solar cells with increasing band gap energies increases the efficiency of the overall device since the solar spectrum is exploited more profitably. The currently most promising realization of this approach is the III-V-based triple-junction solar cell. The state-of-the-art device is a lattice-matched triple-junction solar cell consisting of monolithically stacked $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$, $\text{Ga}_{0.99}\text{In}_{0.01}\text{As}$, and Ge junctions. It has reached conversion efficiencies of 40.1% at concentrations of 135 suns, 1 sun correspond to 1 kW/m^2 , under the AM1.5d low aerosol optical depth spectrum (King, et al., 2007). Yet, detailed-balance (Shockley, et al., 1961) calculations show that the band gap combination of the lattice-matched design is not optimally adjusted to the solar spectrum. This is why different approaches have been suggested how to achieve current-matching (Barnham, et al., 2002). Presently the use of metamorphic structures proves to be the most promising strategy.

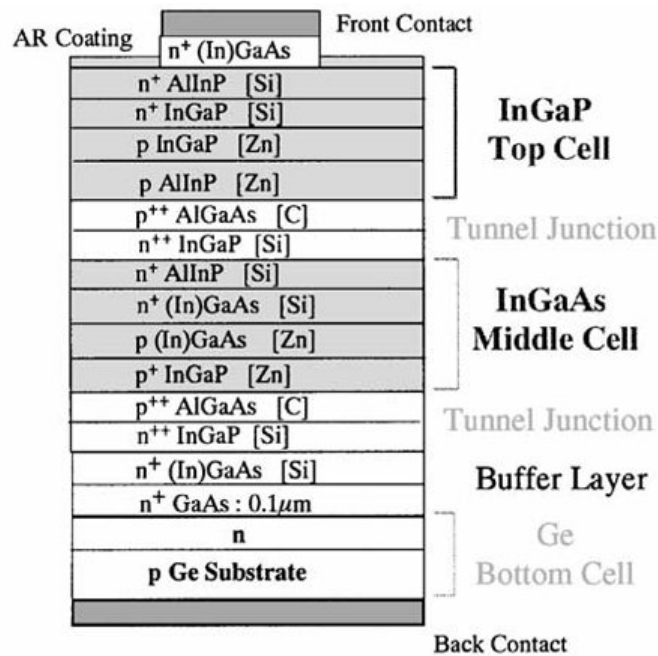
Currently available high-efficiency triple-junction solar cells consist of two III–V semiconductor junctions epitaxially grown lattice-matched

on a single-crystal Ge substrate, which forms the bottom junction as shown in Figure 19. This highly mature latticematched design has achieved 40.1% efficiency at 135 suns concentration (King et al., 2007) using $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$, $\text{Ga}_{0.98}\text{In}_{0.02}\text{As}$, and Ge junctions with the band gap combination of 1.86, 1.39, and 0.67 eV. By growing alloy layers with the same crystal lattice constant as the substrate, most dislocations, which form recombination sites (a loss mechanism), can be avoided. However, the constrained band gap combinations of the lattice matched alloys are not optimal for maximum photovoltaic conversion efficiency of the solar spectrum. Using a semi-empirical model, one has calculated the maximum theoretical efficiency (58%) of a series-connected triple-junction solar cell for a range of band gap combinations assuming GaAs-like material parameters (Friedman, et al., 2006, 2005). While it is unlikely that these actual theoretical efficiencies can be achieved, the relative values are instructive for optimizing a solar cell design. In order to grow a more efficient monolithic solar cell structure with an improved band gap combination, lattice mismatched alloys with low defect densities are required.

Compositionally graded buffer layers can be used to accommodate the lattice-mismatch by the formation of misfit dislocations within the buffer while inhibiting the propagation of these dislocations into the active junction. The resulting structure, incorporating active layers of different lattice constants separated by the graded layer, is commonly referred to as a metamorphic structure (Grider et al., 1990). Metamorphic triple-junction solar cells are beginning to realize their potential for higher efficiencies. An efficiency of 40.7% at 240 suns has been achieved (King et al., 2007) in a metamorphic triple-junction device using a Ge bottom junction and two coupled metamorphic junctions that are both 0.5% misfit from the substrate with the band gaps 1.80, 1.29, and 0.67 eV.

This highly mature lattice matched design has achieved 41.1% efficiency at 135 suns concentration using $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$, $\text{Ga}_{0.98}\text{In}_{0.02}\text{As}$, and Ge junctions

Figure 19. Structure of triple-junction (3J) solar cell on Ge substrate (Yamaguchi, 2002)



with the band gap combination of 1.86, 1.39, and 0.67 eV (Guter, et al., 2009). However, the constrained band gap combinations of the lattice matched alloys are not optimal for maximum photovoltaic conversion efficiency of the solar spectrum as shown in Figure 20. In order to grow a more efficient monolithic solar cell structure with an improve band gap combination; lattice mismatched alloys with low defect densities are required. Compositionally graded buffer layers can be used to accommodate the lattice-mismatch by the formation of misfit dislocations within the buffer while inhibiting the propagation of these dislocations into the active junction. The structure, incorporating active layers of different lattice constants separated by the graded layer, is commonly referred to as a metamorphic structure. Metamorphic triple-junction solar cells are beginning to realize their potential for higher efficiencies. One suggestion to push conversion still further is to add a GaInNAs layer that would absorb photons with energy around 1 eV. However, there are major problems such as high-

density dislocation generation and residual stress in III–V compound films grown on Si substrates, owing to large lattice mismatch and large thermal expansion coefficient differences between III–V compounds and silicon. These problems have prevented solar-cell property improvement. Especially, the density of dislocations short the minority-carrier lifetime in III–V-on-Si. Recently, Tomioka, et al. (Takamoto, et al., 1997) have reported on selective-area growth of vertically aligned GaAs nanowires in SiO₂ template on Si(111) substrate as shown in Figure 21. Small diameter openings in SiO₂ template reduced the antiphase defects and improved the optical properties in the GaAs nanowires. They have realized coherent growth without misfit dislocation at the GaAs/Si interface. These results are promising for future III–V nanowire-based MJ solar cells on Si platforms. One of the most important issues for realizing high-efficiency monolithic-cascade type MJ cells is to achieve optically and electrically low-loss interconnection of sub-cells. Because it is difficult to obtain high tunnelling peak current

Figure 20. Each sub-cell converts different part of solar spectrum. This approach has theoretical efficiency limit of 52 – 56% (depending on light concentration). (Ref. <http://www.fotovoltaika.edu.pl/upload/files/Multi-junction%20solar%20cell.pdf>)

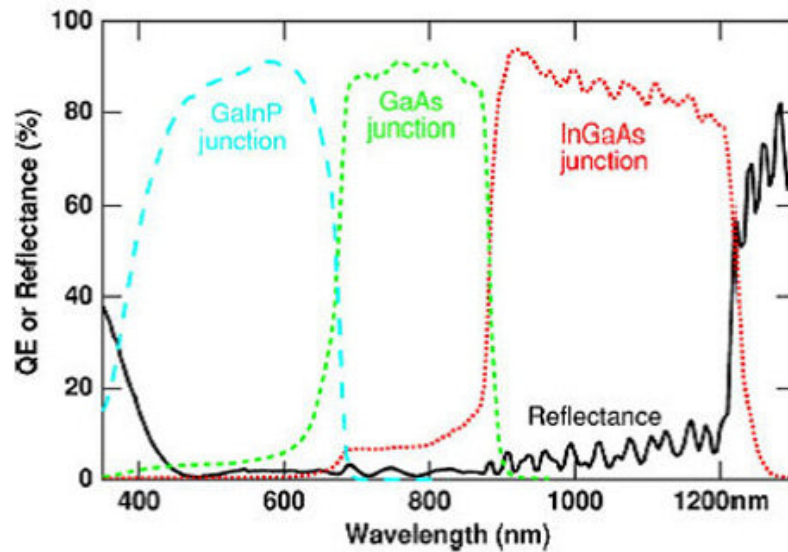
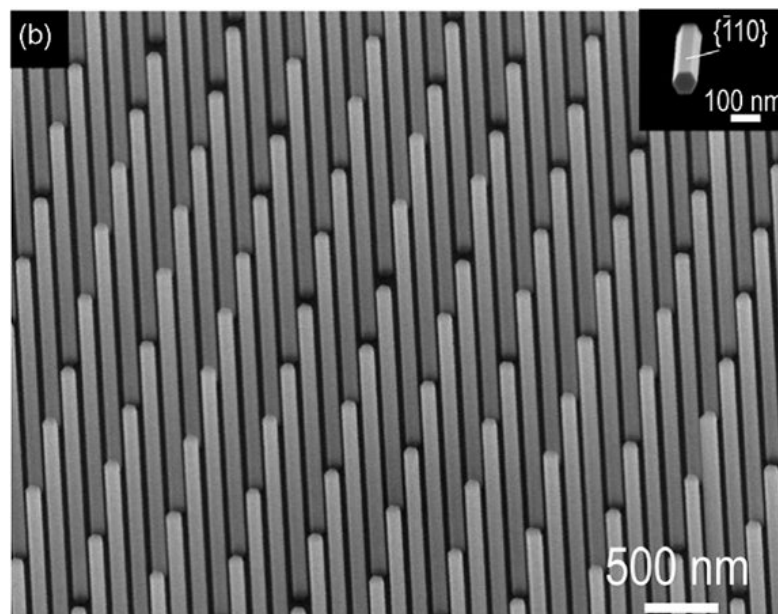


Figure 21. 45-degree tilted view of a scanning electron microscopy image of a GaAs nano-wires array on a Si(111) surface (Takamoto et al., 1997)



with wide gap tunnel junction, thinning depletion layer width by the formation of a highly doped junction is necessary.

Nanocrystalline Hybrid Solar Cells

Nanocrystals (NCs) hybrid photovoltaic (PV) devices offer a potentially low cost alternative to the traditional inorganic counterparts made from materials such as silicon, gallium arsenide, cadmium telluride, copper indium diselenide and other compound semiconductors. Organic-inorganic NCs hybrid PV devices can be processed at room temperature and can be deposited on a large area and/or flexible substrates. At present, one major challenge to hybrid solar cells remains their low conversion efficiencies (up to 5.5% (Saunders, et al., 2008)) and high cost of materials because of the limited use. Theoretical efficiency of hybrid PV devices limit up to 44% (M-Sero, et al., 2009).

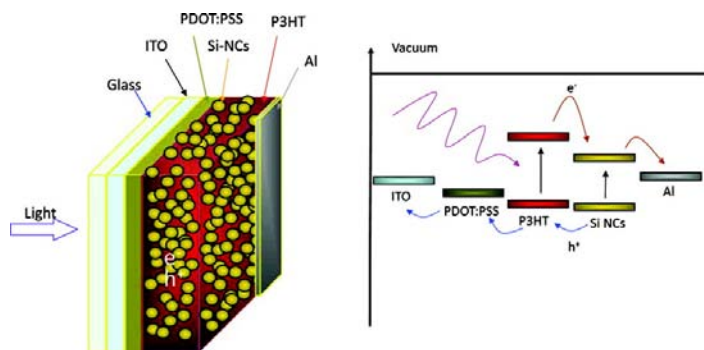
Hybrid solar cells are a mixer of nanocrystals of both organic and inorganic materials. They combine the unique properties of inorganic semiconductor nanocrystals with properties of organic/polymeric materials. Inorganic NCs such as quantum dots (QDs) have also high absorption coefficients and particle size induced tunability of the optical band-gap. When the inorganic NCs size become smaller than an exciton (typically about 10 nm or smaller), their electronic structure will change than their bulk. The electronic and optical properties of such small particles depend not only on the material, of which they are composed but also on their size (Murphy, et al., 2002). Band-gap tuning in inorganic nanocrystals with different sizes can be used for realization of device architectures, such as tandem solar cells in which the different bandgaps can be obtained by modifying only one chemical compound (Green, et al., 1998, 1993). A substantial interfacial area for charge separation is provided by nanocrystals, which have high surface area to volume ratios (Huynh, et al., 1999). Thus, the organic-inorganic NCs

hybrid concept for PV cells is getting interesting and attractive in recent years.

Various promising hybrid solar cells have been reported, including devices which utilize polymer in conjunction with cadmium selenide (CdSe) (Greenham, et al., 1996), lead sulfide (PbS) (Gunesa, et al., 2007), lead selenide (PbSe) (Cui, et al., 2006) and copper indium disulfide (CuInS₂) spherical nanocrystals (Arici, et al., 2003); CdSe nanorods (Huynh, et al., 2002); and CdSe hyper-branched nanocrystals (Gur, et al., 2007). These devices were made by spin-coating nanocrystal/polymer blends onto substrates where they phase segregate at the nanometer length scale to facilitate exciton dissociation and subsequent charge carrier transport. In these hybrid solar cells the organic semiconductor usually acts as the hole-transport medium while the inorganic nanocrystals take the role of electron-transporting medium. Van Hal et al. 2003, reported on hybrid devices based on blends of TiO₂ with MDMO-PPV. To prepare bulk heterojunctions they blended MDMO-PPV with titanium(IV)-isopropoxide, a precursor for preparation of TiO₂ nanocrystals. External quantum efficiency up to 11% has been achieved. Beek et al., 2006, used blends of nanocrystalline zinc oxide (nc-ZnO) and regioregular P3HT from solution to construct hybrid polymer-metal oxide bulk heterojunction solar cells.

Silicon (Si) has enjoyed years of success in the solar cell and microelectronics industries and is a prime candidate for polymer-NCs solar cells given its abundance, nontoxicity, and strong UV absorption. A schematic structure of free-standing silicon NCs and regioregular P3HT to form NC-polymer hybrid solar cells is shown in Figure 22. The energy band diagram of the structure is shown in right. The band alignment of Si and P3HT is such that exciton dissociation at the interface is energetically favourable even for bulk Si and becomes increasingly favourable for quantum-confined Si NCs. This device also has the potential for enhanced exciton dissociation due to the greater interfacial area afforded by the

Figure 22. A Schematic structure of an organic-silicon NCs hybrid solar cell. Thin films of PEDOT:PSS and Si NCs/P3HT were spun sequentially on transparent ITO coated glass substrate. Aluminum metal electrode is deposited on the top. The energy band diagram of the structure is shown in right (Liu, et al., 2009).



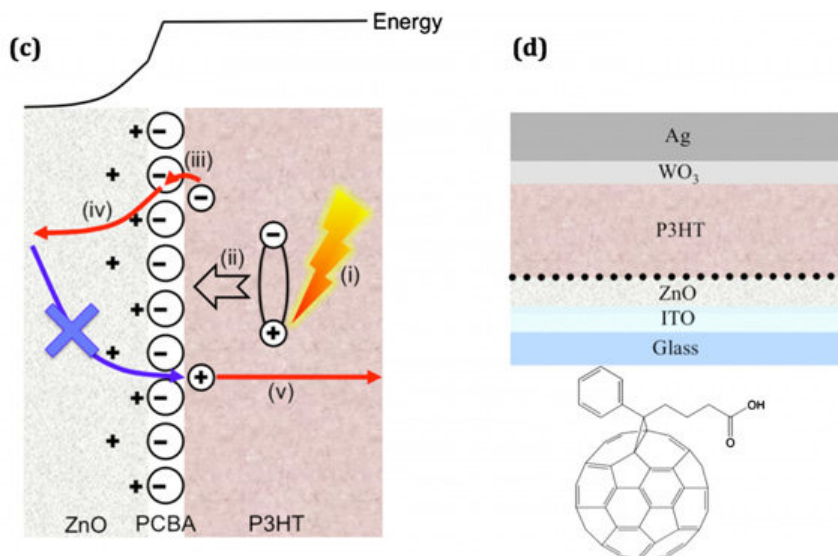
blend architecture. Silicon NCs were synthesized in nonthermal radio frequency plasma via dissociation of silane and collected on mesh filters (Mangolini, et al., 2005). By variation of chamber pressure, precursor flow rate, and rf power, Si NCs can be made with average sizes between 2 to 20 nm. To minimize oxidation, Si NC collection and handling were conducted in a nitrogen purged glovebag.

Recently there is a report to enhance performance of hybrid photovoltaic device, where P3HT is used as active material and a solution-processed thin flat film of ZnO modified by a self-assembled monolayer (SAM) of phenyl-C61-butyric acid (PCBA) is used as electron extracting electrode as shown in Figure 23. Ultraviolet photoemission spectroscopy measurements reveal an increase in the substrate work function from 3.6 to 4.1 eV upon PCBA SAM deposition due to an interfacial dipole pointing away from the ZnO. External quantum efficiency (EQE) of the SAM modified devices reached 9% (Vaynzof, et al., 2010). In these hybrid ZnO-polymer solar cells, photoexcitation creates excitons within the polymer film that may dissociate into free carriers as they reach the interface of the electron accepting metal-oxide ZnO and the polymer. Optimizing exciton dissociation into free carriers at the heterojunction

and reducing recombination losses are crucial for improving device performance. One way to pursue this goal is via molecular surface modification that allows control of the energy level alignment (Lin, et al., 2009).

Compared to the silicon device area, the processing field of organic-inorganic hybrid cells is in its relative infancy. Innovation in organic-inorganic NCs materials selection, device structure and process technology will be essential to develop high efficiency hybrid solar cells. It needs fundamental investigation of new organic and inorganic NCs materials for improved efficiency/stability of cell performance characterisation and modelling, cell structure design improvement, implementation of a range of new ideas relevant to carriers recombination reduction, increase exciton dissociation and improved light trapping in cells and exploration of the potential of a range of “third generation” options as a means of significantly boosting cells performance. A number of ideas for new inorganic quantum dot materials and organic donor/acceptor materials have been proposed in the literature (Thompson, et al., 2005 and Gregg, et al., 2003). A variety of characterisation techniques that have proved valuable in the group’s excitonic quantum dot solar cell work will be applied. The largest potential for current

Figure 23. (c) Mechanism of dipole assisted charge separation at the P3HT/PCBA/ZnO interface: (i) excitation, (ii) exciton migration to the interface, (iii) rapid electron transfer to the PCBA monolayer, (iv) interfacial dipole assisted electron collection in the bulk of the ZnO, and (v) hole collection at the WO₃/Ag electrode. (d) Structure of the inverted hybrid PV device and the chemical structure of the PCBA molecule (Vaynzof, et al., 2010).



output improvement would seem to lie in improved excitonic collection/dissociation by vertical junction structures, essentially the basis of the success of the bulk heterojunction approach, or by parallel multijunctions as well as by improved light-trapping in the devices. Light-trapping in organic and hybrid cells does not appear to have been fully exploited to date. Light-trapping in this case can not only improve light absorption and hence current output but also can reduce carriers' radiative recombination and hence improve voltage output.

There is a lack of information in the literature about the structure of the organic-NCs interface in hybrid PV cells. The nature of the organic-NCs interaction and the extent of adsorption will affect dispersion stability and also photoactive layer morphology. It will also play an important role in charge transport across the organic-NCs interface. Good interfacial contact is essential in order to maximise the interfacial area and minimise the series resistance across the cell. It is

very important to study on organic-NCs interface to enhance exciton dissociation and suppress carrier recombination. Normally, free carriers are produced when the band offsets are greater than the exciton dissociation energy. Controlling aggregation within organic/NCs/solvent mixture to obtain morphological optimisation will improve the hybrid cells efficiency. Increasing the dispersion stability of organic/NCs/solvent mixtures should improve the morphology of the photoactive layer and improve the efficiency. A key challenge for organic-NCs hybrid PV cells is to control the aggregation within the NCs phase in order to produce equilibrium morphologies to minimise recombination losses.

Third Generation Approaches

In the present terminology, "third generation" refers to approaches fundamentally capable of higher performance than from a single junction device. The tandem cell stacks of the previous

section are the most common example of a third generation approach as shown in Figure 24. This approach is not well suited for organic-inorganic NCs hybrid cells due to the difficulty in identifying stable organic material with a low bandgap, a difficulty the combined organic/inorganic QD approach, described above, may circumvent.

Other “third generation” approaches may be better suited to hybrid cells. One is up-conversion, given the better stability demonstrated by different bandgap hybrid devices. Similarly, intermediate band cell concepts are particularly appropriate for organic-inorganic hybrid cells. The instability of narrow band gap organic compounds tends to dictate large band gap absorbers. Whilst these bandgaps are above the optimum for a single bandgap device they are ideal for a multiple level up-converter or an intermediate band approach. Also the relatively discrete nature of energy levels in organic molecules (even for partially delocalised molecules) is just the prop-

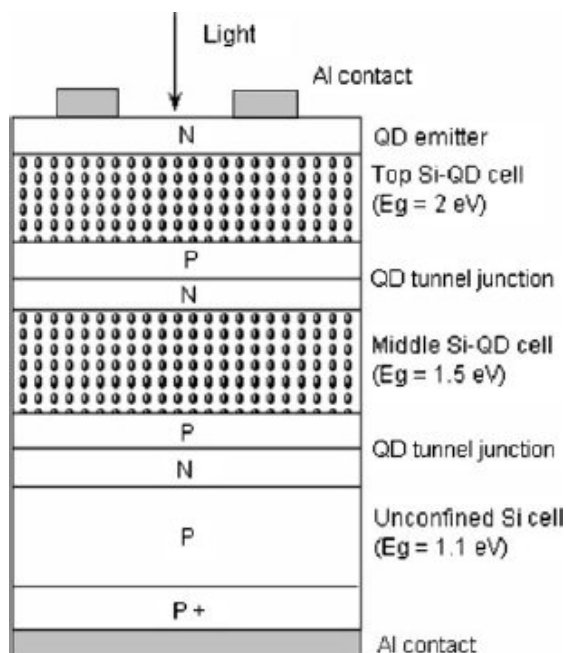
erty required for the long intermediate level lifetimes needed in these approaches.

Hot-Carrier Solar Cells

Normally, theoretical analysis of conventional solar cells is based on particle conservation for each absorbed photon, one electron-hole pair is generated within the device and, for each electron-hole pair that recombines via radiative recombination and a single photon is emitted. However, energy conservation is not applied between the electron-hole pairs that are withdrawn and the absorbed photons because of energy losses by thermalisation of carriers with the lattice. Electron-phonon scattering produces separate Fermi distributions for holes in the valence band and electrons in the conduction band at the lattice temperature with separate Fermi energies for each band. Since the Fermi energy of the conduction band distribution is larger than the Fermi energy for the valence band, the chemical potential of the electron-hole pairs is greater than zero. This is an essential result for conventional solar cells, since the maximum electrical energy obtainable per extracted electron-hole pair is equal to their chemical potential.

In analysing the potential of obtaining high efficiencies by using hot carrier solar cells, Ross and Nozik considered the generation of electron-hole pairs in solids where thermalisation of carriers with the lattice is suppressed (Ross, et al., 1982). They applied, in addition to particle conservation, energy conservation between the photons and electron-hole pairs. Electron-electron scattering within a band leads to Fermi distributions for the electrons and the holes which have a higher temperature than the lattice temperature and a negative chemical potential of electron-hole pairs for best performance. Electron-hole pairs are then removed at a single energy level where the Fermi distributions in the absorber and the contacts are equal, to achieve the highest possible efficiency for the energy conversion process. Owing to the

Figure 24. A schematic diagram of an all-Si quantum dot super lattice tandem solar cell (Aliberti, et al., 2010; Dawei, et al., 2010)



monoenergetic extraction of electrons and holes from an ideal hot-carrier solar cell, the net absorbed energy flux is converted to electrical energy at the Carnot efficiency, irrespective of whether electron–hole pairs are conserved. In the case where the chemical potential of the absorber is negative, the emitted photon flux is less than from a thermal emitter with zero chemical potential at the same temperature. This means that the overall efficiency of the hot-carrier cell is somewhat smaller under the assumption of non-negligible impact ionisation, particularly for non-concentrated radiation.

The hot carrier solar cells concept provides an attractive solution of the conversion efficiency of Shockley–Queisser limit (Shockley, et al., 1961). Hot carrier solar cells allow efficiency enhancement by converting the excess carrier kinetic energy, which is normally lost as heat because of carrier thermalization, into electrical work. Two loss processes (i) a heat transfer to lattice due to phonon emission and (ii) a heat leakage to the contacts carried by charge carriers are extracted from the absorber. These loss can be minimized when the contacts are energy selective, i.e., allow carrier transmission at a single energy level (Würfel, 1997). The use of nanostructured semiconductors was found to reduce the electron cooling rate related to phonon emission (Rosenwaks, et al., 1993). On the contact side, the solution proposed so far showed the technological difficulty to achieve a good selectivity and high current densities (Jiang, et al., 2004).

The first model of a hot carrier solar cell was proposed considering no carrier thermalization in the absorber and perfectly selective contacts (Würfel, et al., 2005). This model gives optimal efficiency up to 86% under maximal concentration (≈ 46000 suns). Other models, that consider thermalization in the absorber and ideal selective contacts, with a thermalization rate independent of the carrier temperature or using a thermalization rate determined from experimental data that depends on the carrier temperature, still predict efficiencies in the 50% range or higher (Takeda et

al., 2009 and Conibeer, et al., 2008). In the latter, the energy loss rate can be fitted to experimental data by the following equation:

$$P_{th} = Q_{Th}(T_H - T) \exp\left(-\frac{E_p}{k_B T_H}\right); \quad (1)$$

where Q_{Th} is a thermalization coefficient in watt kelvin per square centimeter and is a material constant, E_p is the zone center LO phonon energy, and T_H and T are the carrier and lattice temperature, respectively. A model considering nonideal selective contacts has also been proposed but with neglected thermalization in the absorber, and only in the limit of a band gap equal to zero (O'Dwyer, et al., 2008). The charge and energy current in that case are given, following the Landauer formalism by the following expressions (Imry, et al., 1999):

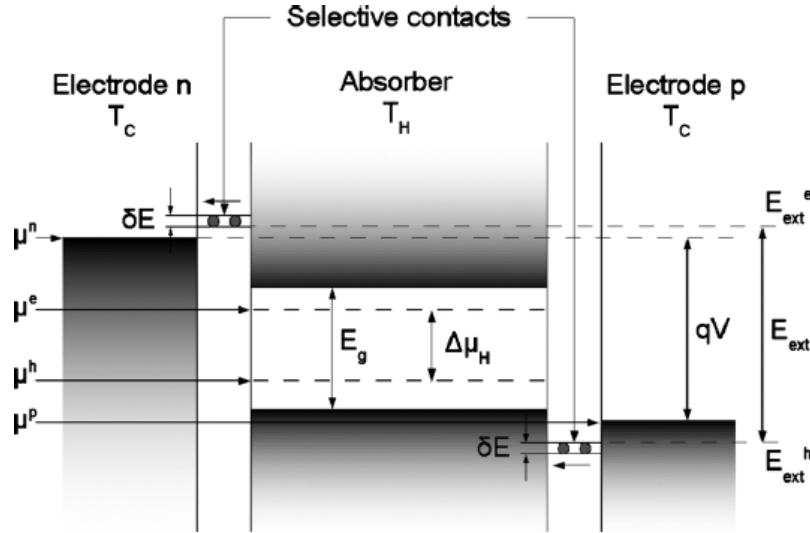
$$J^{e,h} = \frac{2N}{h} \int_0^\infty \tau^{e,h}(E) [f_H^{e,h}(E) - f_C^{e,h}(E)] dE; \quad (2)$$

$$P^{e,h} = \frac{2N}{h} \int_0^\infty \tau^{e,h}(E) [f_H^{e,h}(E) - f_C^{e,h}(E)] E dE; \quad (3)$$

where $\tau^{e,h}(E)$ is the electron or hole contact transmissivity which is the probability for an electron (or hole) having an energy E to cross the contact, and N is the contact degeneracy (i.e., the areal concentration of contact energy levels). $f_H^{e,h}$ and $f_C^{e,h}$ are the Fermi–Dirac distribution functions for electrons/holes in the absorber with the quasi-Fermi level splitting $\Delta\mu_H$ as chemical potential, and in the electrodes with the voltage qV as chemical potential, respectively (see Figure 25).

These two thermalization processes are not independent and have to be considered simultaneously. The thermal losses in the absorber and at the contacts are compared for different contact selectivity and thermalization rates. This model is based on a detailed balance model described

Figure 25. Schematic of a hot carrier solar cell. Electron–hole pairs are photogenerated in the absorber and kept hot (temperature $T_H > T_C$, T_C is the ambient temperature) where the thermalization rate with the lattice is slow enough. They are ideally extracted through energy selective contacts with a narrow transmission range δE for minimal heat flux with an extraction energy close to $E_{ext} = E_{ext}^e - E_{ext}^h$. $\mu^{e,h}$ are the electron and hole chemical potential, respectively, in the absorber, and $\mu^{n,p}$ are the Fermi levels in the electrodes (Le Bris, et al., 2010).



by Ross and Nozik, 1982, consisting in a charge and energy balance between electron–hole pairs generation on one side, recombination and extraction (electric current) on the other side. The absorbed photon current J_{abs} and power P_{abs} are distributed as follows:

$$J_{abs} = J^{e,h} + (1 + \eta_{NR})J_{em}; \quad (4)$$

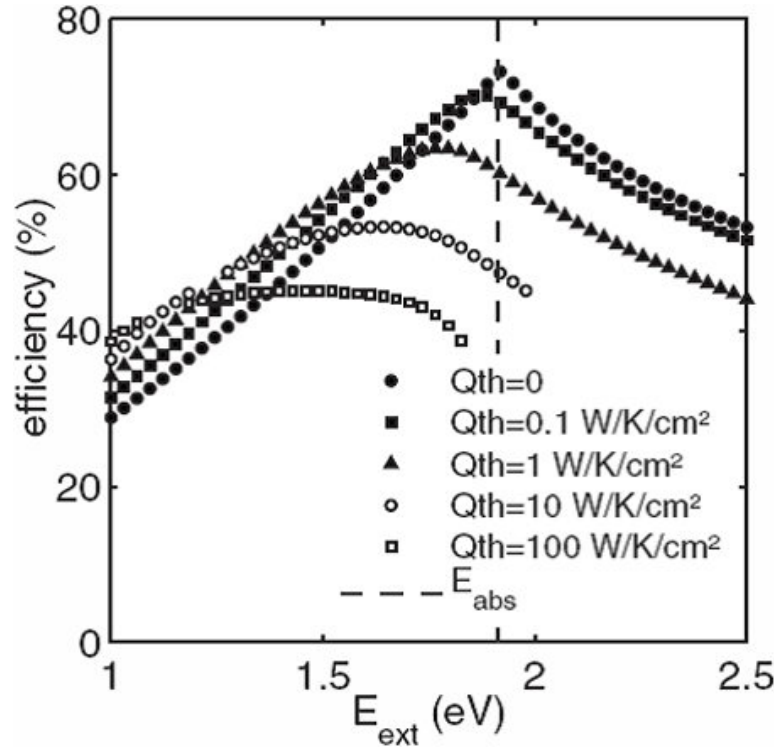
$$P_{abs} = P^e + P^h + P_{em} + P_{th}; \quad (5)$$

where $J_{e,h}$ is the collected electron or hole current at the contact, P^e and P^h are the energy current at the electron contact and the hole contact, respectively, J_{em} and P_{em} are the charge and energy current lost by radiative recombination, P_{th} is the heat loss carried by phonons, and η_{NR} is the nonradiative recombination rate. The electric current is given by $I = qJ^e = qJ^h$ and the power transmitted by the contact $P = P^e + P^h$ is divided between electrical

power $W = IV$ and a heat flow carried by the collected carriers $P_{contact} = P^e + P^h - IV$. Generation and recombination charge and energy current are given by a generalized Planck law (Würfel, 1982).

If one consider conduction band and valence band are symmetrical, then two types of carriers can be considered identical with $T^e = T^h = T^H$, and $\mu^e = -\mu^h = \Delta\mu_H/2$ (see Figure 25 for definition). This assumption enables more straight forward interpretation of the influence of contact transmissivity on the device behavior, with fewer parameters. Similarly, the electron and hole transmissivities are taken one in the range $(E_{ext}^e, E_{ext}^e + \delta E)$ and $(E_{ext}^h, E_{ext}^h - \delta E)$, respectively (see Figure 25), zero outside. Finally, particle conservation is also assumed which means that nonradiative recombination are considered negligible $\eta_{NR}=0$ (Ross, et al., 1982 and Würfel, et al, 2005). Solving above equations, one can obtain the current-voltage characteristic of the device under illumination. The influence of the extraction energy E_{ext} and

Figure 26. Conversion efficiency vs extraction energy at various thermalization rates, for a 1 eV band gap absorber under full concentration with highly selective contacts ($\delta E = 1$ meV). $Q_{Th} = 0$, means no thermalization in the absorber, $Q_{Th} = 100$ W/K/cm²: fast thermalization. A value of $Q_{Th} = 10$ W/K/cm² was measured with GaAs quantum wells samples. E_{abs} is the average energy of absorbed photons, i.e., 1.91 eV for a 6000 K black body spectrum (Le Bris, et al., 2010).



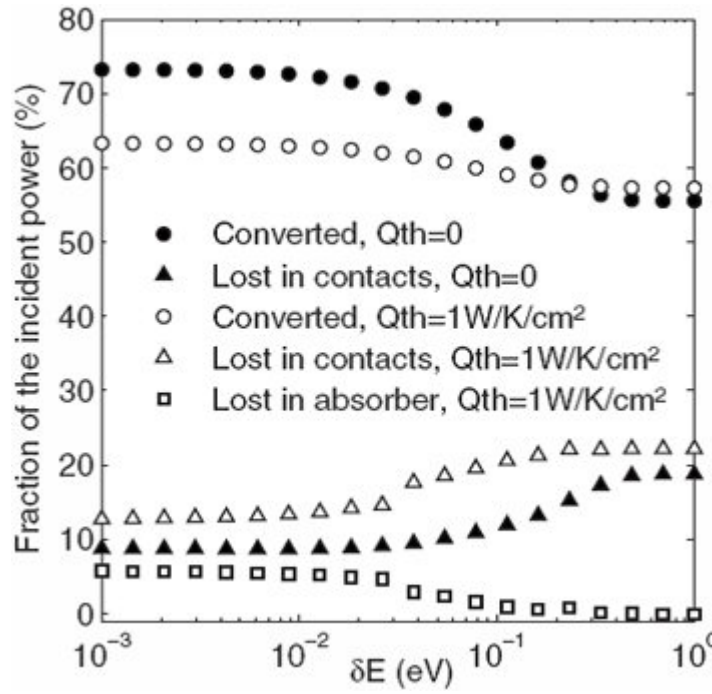
the contact selectivity δE on the conversion efficiency can hence be studied while heat losses in the absorber and through the contacts can be compared for various thermalization rates. In ideal conditions means no thermal losses in the absorber, the optimal extraction energy is equal to the average energy of absorbed photon (thus equal to the average energy of photogenerated electron–hole pairs) for maximal power conversion efficiency. In that case, carriers are generated and extracted at the same average energy.

Figure 26 presents the efficiency as a function of the extraction energy for different thermalization rates. A value of $Q_{Th} = 10$ W/K/cm² corresponds to a thermalization rate measured on GaAs quantum wells and a value of about 1000 W/K/cm² is typical for bulk GaAs (Guillemoles,

et al., 2005). Value with $Q_{Th} \gg 100$ W/K/cm² the carrier population is almost fully thermalized.

For extraction energy below the carrier average energy, large currents are achievable but the energy extracted per collected electron–hole pair is lower than the available energy, resulting in a limited external voltage. For extraction energy above the carrier average energy, a higher voltage is possible but the available energy in the electron gas is not sufficient for all carriers to be extracted, resulting in limited current. An optimal value of the extraction energy is found that decreases with the increase in the thermalization rate in the absorber. The second important parameter is the contact selectivity, related to the contact transmission energy range. It controls the heat flux that accompanies the charge current at both

Figure 27. Efficiency (circles) and losses (heat losses in absorber: squares, heat flux at contacts: up triangles) vs contact selectivity for a 1 eV absorber under full concentration of sun light with suppressed thermalization (filled markers) or with a thermalization factor $Q_{Th} = 1 \text{ W/K/cm}^2$ (empty markers). The extraction energy is optimized for each value of the thermalization factor and for a transmission range $\delta E = 1 \text{ meV}$.



contacts. For perfectly selective contacts, the heat flux is minimal and is given by the difference between the power extracted $E_{ext}J$ and the electric power IV , J being the charge current, and I the electric current ($I=qJ$). Finally, the heat losses are given by Equation 3 $P_{contact} = (E_{ext} - qV)J$ in this case. For nonideal selective contacts, with non-vanishing transmission energy range δE , Equation 3 applies to determine the heat losses at the contacts.

Figure 27 presents the efficiency and losses as a function of the contact selectivity for two values of electron thermalization rates. For very narrow selective contacts ($\delta E \ll k_B T$) the heat flux at the contacts is limited and the efficiency is that of a hot carrier solar cell with ideally selective contacts (Würfel, et al., 2005 and Conibeer, et al., 2008). When δE becomes comparable with

$k_B T$, the heat flux increases significantly and the efficiency decreases. For $\delta E \gg k_B T$, the heat flux saturates. But even though the contacts are not selective, the heat flux is limited by the small carrier density at energies above the extraction energy. The efficiency with high-pass contacts rather than bandpass is still higher than the Shockley–Queisser limit where the absorber’s band gap E_g limits both the output current and voltage of the device.

For a thermalization coefficient $Q_{Th} = 1 \text{ W/K/cm}^2$, the efficiency drop with the broadening of the transmission range is smaller than in the case of infinitely slow thermalization ($Q_{Th} = 0$). When the heat flux at the contacts increases because of a broader transmission range the carrier temperature decreases, leading to reduced heat transfer to phonons, thus limiting the losses. For a trans-

mission range $\delta E \gg k_B T_H$, i.e., a semiselective contacts, allowing transmission above E_{ext} , and with a small thermalization factor $Q_{\text{th}} = 1 \text{ W/K/cm}^2$, an efficiency above 50% is achievable.

FUTURE RESEARCH DIRECTIONS

Through PV research and development (R&D) and mass deployment efforts, solar cell manufacturing costs have been reduced. It is crucial for PV power generation to be cost competitive to the existing conventional residential power generation. At present the PV electricity generation cost is still higher than conventional residential power. Energy resource and global environmental issues have emerged; the importance of PV systems is ever increasing. Further efforts are required to create a full-scale market for PV systems as well as to elevate the status of PV power generation to an established energy supply technology. The R&D on elemental device technologies, such as thin-film solar cells and tandem solar cells, etc. is important to achieve the goal. The R&D for practical uses will also need to be enhanced for mass production and mass deployment. Objectives are subsequent for next-generation technologies to achieve the targeted cost reductions. The future PV research direction should cover several different projects categories: crystalline silicon solar cells, thin-film silicon solar cells; organic solar cells, multi-junction tandem solar cells, Nano-crystalline solar cells and hot-carrier solar cells. The outline of the research in each category is as follows:

Crystalline silicon solar cells: In section 2 some important areas of on-going research for crystalline silicon solar cells are presented. The main objectives of this research are to reduce the consumption of silicon material in addition to increase conversion efficiency greater than the present value to reduce production costs. The redesigning of emitter and front and back metal contact of PV devices, used n-silicon substrate, use

laser doped technology for selective emitter solar cells, use inkjet printing technology for solar cell fabrication, use low quality silicon ingot such as multi-crystalline silicon wafers, slicing ingots to obtain ultra-thin wafers, and surface passivation of multi-crystalline silicon wafers need to be investigated.

Thin-film solar cells: In section 3 some outlines of the preliminary research for thin-film solar cells are discussed. Poly-crystalline silicon thin film solar cell is one of the important areas to investigate, such as glass substrate texturing for improve light trapping, different crystallization technology, different methods of silicon thin film deposition, re-design of devices structure, develop new method to fabricate high efficiency device, etc. CdS/CdTe thin film solar cells is the another area to investigate to improve the device efficiency, such as re-design device structure, improve light trapping, increase crystallization of CdS and CdTe films, clear understanding the mechanism of cell performance, etc.

Organic solar cells: Organic solar cell is the new area of research for alternative low cost PV technology. But there are lots of challenges to solve before making this technology commercially available, such as improve the device conversion efficiency and improve the device stability and durability. To improve the device efficiency it is important to control the morphology of donor and acceptor in the blended active layer, improve the light trapping, enhance the exciton dissociation rates, etc. To improve the device stability and durability it is very important to develop new device structure, develop encapsulation, understand the mechanism of degrading, etc.

Multi-junction tandem solar cells: In section 4 multi-junction tandem solar cells are explained. This device on Si substrates have a great potential for high-efficiency, low-cost, lightweight and large-area space cells. However, there are major problems such as high-density dislocation generation and residual stress in III–V compound films grown on Si substrates, owing to large lattice

mismatch and large thermal expansion coefficient differences between III–V compounds and silicon. It is important to re-design the device structure to control the interconnection dislocation density to improve the device conversion efficiency.

Nano-crystalline solar cells: Nanocrystalline (NC) PV devices have the potential to develop low cost PV technology. Inorganic NC such as quantum dot materials have high light absorption coefficient and particle size induced tunability of the optical band-gap. Band gap tuning can be used for device architectures, such as tandem solar cells in organic or inorganic matrix. It needs to investigate a range of suitable NC materials, new device structure, increase exciton dissociation, light trapping, etc. to improve the conversion efficiency.

Hot-carrier solar cells: Hot carrier solar cells concept is explain in section 4.3 which can provides an attractive solution of the conversion efficiency of Shockley–Queisser limit (31%). This concept allow efficiency enhancement by converting the excess carrier kinetic energy, which is normally lost as heat because of carrier thermalization, into electrical work. The conversion efficiency can go over 70% if we can use the loss energy into PV output. It needs to develop new device structure with suitable materials and investigate the device performance to improve the conversion efficiency.

CONCLUSION

The PV R&D over the past 30 years has produced significant achievements, such as improve conversion efficiency and the establishment of the technological foundation for the solar cell production. New seed search research for PV technology need to continue on a long-term basis. However, since PV power generation needs to be one of the main primary energy supply technologies, further PV R&D is required in various areas, such as efficiency improvements, low-cost manufacturing process and system technologies. Therefore, it is

essential to make further technical breakthroughs in order to realize innovative technologies. It is also important to collaborate with other renewable energy technology fields.

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KEY TERMS AND DEFINITIONS

2nd-Generation Solar Cells: Thin film materials types photovoltaic devices.

3rd-Generation Solar Cells: Novel solar cell concepts capable of 1-sun efficiencies beyond the Shockley Queisser limit of 31%.

Conversion Efficiency: The percentage of sun light energy converts into electrical energy.

First-Generation Solar Cells: Crystalline silicon p-n junction type photovoltaic devices.

Glass Texturing: Create rough surfaces of glass substrates for thin film solar cells to increase the light trapping to increase devices conversion efficiency.

Organic Photovoltaic: Polymer materials based photovoltaic devices.

Photovoltaic Device: A device that can convert sun-light energy into electrical power energy.

Tandem Solar Cells: Multi-junction solar cells to use whole sun light spectrum for the super-high efficiency photovoltaic devices.

Chapter 6

Nanotechnology for Photovoltaic Energy: Challenges and Potentials

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ABSTRACT

Solar radiation is plentiful and a clean source of power. However, despite the first practical use of silicon based solar cell more than 50 years ago, it has not been exploited to its full potential due to the high cost of electrical conversion on a per Watt basis. Many new kinds of photovoltaic cells such as multi-junction solar cells dye –sensitized solar cells and organic solar cell incorporating element of nanotechnology have been proposed to increase the efficiency and reduce the cost. Nanotechnology, in the form of quantum dots, nanorods, nanotubes, and grapheme, has been shown to enhance absorption of sunlight, makes low cost flexible solar panels and increases the efficiency of photovoltaic cells. The chapter reviews the state of current photovoltaic cells and challenges it presents. It also discusses the use of nanotechnology in the application of photovoltaic cells and future research directions to improve the efficiency of solar cells and reduce the cost.

INTRODUCTION

Photovoltaic is derived from Photo meaning “light” and voltaic meaning “electric” and is defined as the conversion of sunlight to electricity through a photovoltaic cell (PV). It was first discovered by French physicist Alexandre-Edmond

Becquere (1839). The first Solar cell was built by Fritts (1883), who coated the semiconductor selenium with an extremely thin layer of gold to form the junctions (1% efficient). The modern age of solar power technology started when Chapin, Fuller, & Pearson (1954) from Bell Laboratories, discovered that silicon doped with certain impuri-

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ties was able to generate electricity for satellites. This device originally known as the solar battery is currently called Solar cell, exploited the principle of P-N junction. Initially the energy conversion of the cell, was 6% and reached 11% by the year 1957 and 14% by the year 1960 (Pearson, 1957; Rappaport, 1961). Photovoltaic cell is a non-mechanical device usually made from silicon which creates an electron imbalance across the cell and produces direct current (DC) as a result of incident sunlight. To convert DC current into workable alternating current (AC) electricity a device known as power converter is used. Solar energy or solar radiation can also be used for thermal energy source.

The world current energy consumption is 4.1×10^{20} Joules/year which is equivalent to a continuous power consumption of 13 trillion watts or 13 terra watts (TW). The earth surface receives an average of 120,000 TW from the sun, ignoring the energy being scattered by the atmosphere and clouds. Thus with Solar cells as low as 10% conversion efficiency, the world's energy needs can be satisfied with solar panels covering 0.16% of earth surface which would supply 20 TW of power. In US it will take 1.6% of the land area to meet the country domestic needs ("Basic Research Needs for Solar Energy Utilization," 2005). According to Pike Research forecasts, the worldwide demand for solar energy will nearly double between 2010 and 2013, reaching 19.3 Giga watts by the end of that period, caused by the shift of solar industry from supply-constrained to demand-driven over the past two years. This shift is driven by a new abundance of polysilicon, as well as the effects of the worldwide financial crisis, and the plunging price of solar modules. This market realignment will set the stage for a new era of solar growth over the next several years ("Global Solar Energy Outlook," 2010).

Photovoltaic energy as an alternative renewable energy source is emerging as a viable solution to energy problems worldwide. Despite its immense potential it is still a long way from

becoming the world's major energy source because of many challenges it presents in its implementation. This includes higher cost of making large silicon solar panels and inefficient Solar cells due to inadequate absorption of sunlight and low efficiency of 31% set by Shockley and Queisser (1961) for a single semiconductor junction. The high price for Solar cells is largely due to the use of expensive substrate materials and costly microfabrication processing. The efficiency of thin film photovoltaic cell increased from 10% in 1970 to over 24% in the most recent years by the use of new photovoltaic materials. Ongoing research in photovoltaic energy and new developments in nanotechnology is overcoming some of these challenges. Nanotechnology in the form of nanoparticles, nanowires and nanostructures has been shown to enhance absorption of sunlight, make low cost flexible solar panels and increase the efficiency of photovoltaic cells beyond Shockley and Queisser (1961) limit by using multiple exciton generation in nanostructures. The advantages of nanotechnology based Solar cells also reduce manufacturing costs as a result of using a low temperature manufacturing process instead of high temperature vacuum deposition process typically used to produce conventional crystalline semiconductor based Solar cells.

The problem of making large and costly silicon solar panels is overcome by making Solar cells so thin that they can be painted and printed onto rolls of thin film in the form of a foil or spray which can be produced cheaply and quickly. The cell uses alloy of copper called copper Indium Gallium Diselenide (CIGS) and is as efficient as silicon but is cheaper and lighter (Marshall & Bazeley, 2006). A new method of increasing the absorption of sunlight is obtained by combining silicon with low cost plastic which improves the efficiency and reduces the cost of photovoltaic cells. These cells consist of a large number of very small wires made of 2% silicon grown on 98% of plastic substrate. The dimensions of silicon wires range from 30 to 100 μm in length, and 1 μm in

diameter. Each wire is coated with antireflective coating so that light can easily penetrate them; bounce around among the forest of silicon wires until it is absorbed. The silicon-wire array has shown to absorb up to 96% of incident sunlight at a single wavelength and 85% of total collecting sunlight. These panels are flexible and can be applied to any surface to collect solar energy (Johnson, 2010). Nanorods have also been used to increase absorption in solar panels designed to absorb sunlight at a single angle by including layers of nanorods in the spray which forms a multi-layer coating that works like a series of funnels. The top layer of nanorods takes the light hitting the panel at a wide angle and redirects the direction causing it to always hit at the proper angle for maximum absorption instead of a panel's need to rotate with the sun ("Nanotechnology and Solar Energy," n.d).

Nanowires of different sizes have been used to extend the range of sunlight absorption resulting in increase in the conversion efficiency. The thinner 10 nm wire is good for absorbing light in the visible range and larger nanowires are good for longer wavelength stretching into the infrared (invisible) part of the spectrum. This means that these wires can be used to detect and absorb light even in the cloudy weather or in the dark (Orenstein, 2009). Research is ongoing in the use of quantum dots for achieving photon multiplication and making hot-carrier cells. In photon multiplication up to seven electrons-hole pair are achieved for each incoming photon, thus increasing the Solar cells efficiencies up to 40%. The hot carrier cells are made by making use of extra energy lost as heat in the photon-electron conversion (Johnson, 2008).

The purpose of this chapter is to investigate the use of nanotechnology in the implementation of low cost, highly efficient and easy to implement photovoltaic cells. The chapter also discusses the current state of photovoltaic cells and challenges it presents. The chapter starts with introduction as section 1. Section 2 discusses the solar radiation and its characteristics. Section 3 discusses

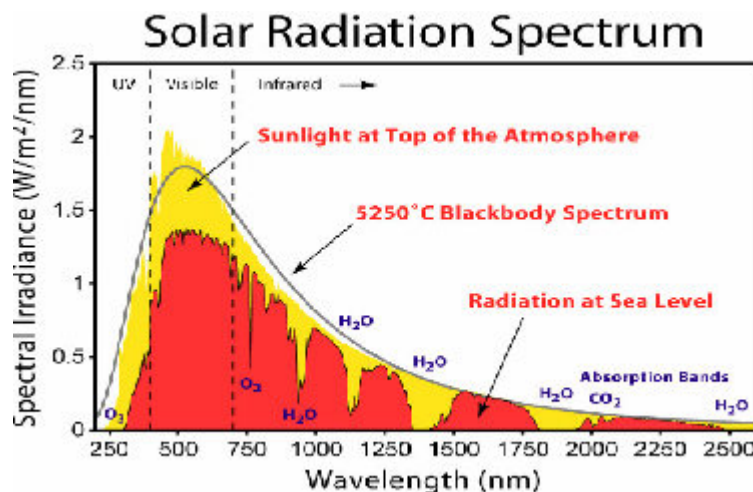
the current state and challenges of photovoltaic cells. Section 4 discusses nanotechnology based solution to improve the Solar cells and details of different photovoltaic cells based on nanotechnology. Section 5 discusses the use of graphene for Solar cells and graphene based photovoltaic cells. The chapter is concluded with a conclusion and list of references.

SOLAR RADIATION

Solar energy is the most important source of regenerative energy which is also the source of waterpower, wind and biomass. The total power radiated into space from the Sun is about 3.86×10^{26} watts. Most of this radiation is in the visible and infrared part of the electromagnetic spectrum, with less than 1% emitted in the radio, UV and X-ray spectral bands. The annual energy input of solar irradiation on Earth (5% UV, 43% visible, 52% IR) exceeds the world's yearly energy consumption by several thousand times. Since the Sun's distance is 150 million kilometers from the Earth and 6300 km radius of Earth, only 0.000000045% of this power is intercepted by our planet which amounts to a massive 1.75×10^{17} watts. The solar constant defined as power of the sun at the earth per square meter is approximately 1370 watts per square meter (W m^{-2}). The solar constant varies by $\pm 3\%$ because of the Earth's slightly elliptical orbit around the Sun. On the surface of the earth on a clear day, at noon, the direct beam radiation will be approximately 1000 watts/ m^2 for many locations (Shaw, 1953).

The different regions of solar radiation shown in Figure 1 are described by their wavelength range within the broad band range of 0.20 to 4.0 μm . This includes visible and near-visible (ultraviolet and near-infrared) radiation emitted from the Sun as: Ultraviolet: 0.20 – 0.39 μm , Visible: 0.39 – 0.78 μm , Near-Infrared: 0.78 – 4.00 μm , Infrared: 4.00 – 100.00 μm . The availability of Sun energy is affected by location, season, and time of day, all

Figure 1. Solar radiation (© 2007, Robert A Rohde, Global warming art; Retrieved from http://www.globalwarmingart.com/wiki/File:Solar_Spectrum.png)



of which can be readily determined. However, the biggest factors affecting the available energy are cloud cover and other meteorological conditions which vary with location and time.

PRINCIPAL OF PHOTOVOLTAIC CELL

The principle of Solar cell is based on the well known photoelectric effect and semiconductor physics. In semiconductor physics a photon with energy greater than bandgap energy ($h\nu > E_{\text{gap}}$) incident on a semiconductor can excite electrons from the valence band to conduction band, allowing for current to flow. The energy of photon which appears in the form of packets of energy is given by $E = h\nu$, where h is Planck constant ($6.626 \cdot 10^{-34}$ Ws²), and ν is frequency in Hertz. The maximum current density is given by the flux created by that of incident photons energy. The excess energy which is the difference of incident photon energy and energy gap ($h\nu - E_{\text{gap}}$) is lost in the form of heat or thermalization and is therefore wasted.

A Solar cell is essentially a large area p-n junction diode. Energy from the incident photons

creates excitation of the electron to the conduction band leaving behind a hole in the valence band resulting into electron-hole pairs or excitons in the case of organic semiconductors. The electron-hole pairs separate at the p-n junction with electrons and holes diffusing across depletion zone to the p-type and n-type region respectively. This flow of charge carriers due to thermal energy generates a current which is essentially due to electrons in the conduction band that moves through the semiconducting material. The current generated as a result of incident photons on p-n junction depends directly on the mobility of the carriers in the material and the exposed surface area of the junction ("Basic Research Needs for Solar Energy Utilization," 2005). The amount of current generated by photon excitation in a photovoltaic cell at a given temperature is affected first by the intensity of the incident light and second by the wavelength of the incident light. The materials used in photovoltaic cells exhibit a varying sensitivity with respect to the absorption of photons at given wavelengths because of the different spectral responses to incident light. For each semiconductor material there is a cut off frequency or incident radiation threshold frequency, below which no photovoltaic

effect will take place. Above the threshold frequency, the kinetic energy of the photogenerated electron will vary according to the wavelength of the incident radiation without any relation to the change in the intensity of light. The increase in the intensity of light will proportionally increase the rate of photogeneration in the material used for photovoltaic cell. The light absorbed by a Solar cell in real life application is a combination of direct solar radiation, as well as diffused light bounced off surrounding surfaces. As a result Solar cells are often coated with anti-reflective material to absorb the maximum amount of radiation possible.

3.1 Characteristics of Photovoltaic Cell

Photovoltaic cells (PV) can be modeled as a current source in parallel with a diode. When there is no light present to generate any current, the PV cell behaves like a diode. As the intensity of incident light increases, current is generated by the PV cell, as shown in Figure 2. ("Photovoltaic Cell I-V Characterization," 2009)

Equation of the ideal Solar cell model, is given by (Lenardie, 2010)

$$I = I_{ph} - I_s \left[e^{V/(mV_T)} - 1 \right]$$

I_{ph} is photocurrent in amperes, I_s is reverse saturation current in amperes (approximately

range $10^{-8}/m^2$), V is diode voltage, V_T is thermal voltage = kT/q (25.7 mV at 25°C), m is diode ideality factor = $1 \dots 5 \times V_T$ (-) ($m=1$ for ideal diode)

Efficiency of Photovoltaic cell: It is defined as the ratio of electrical power (P_{out}) produced by a photovoltaic cell at any instant to the power of the solar input (P_{in}) which is sunlight striking the cell measured in W/m^2 . P_{out} can be taken to be P_{MAX} since the Solar cell can be operated up to its maximum power output to get the maximum efficiency.

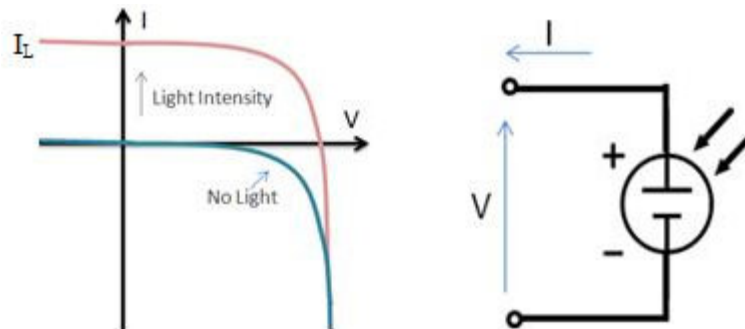
$$\eta = \frac{P_{out}}{P_{in}} \rightarrow \eta_{MAX} = \frac{P_{MAX}}{P_{in}}$$

η_{MAX} (maximum efficiency) found from the light test is an indication of the performance of the device under test. It can be affected by ambient conditions such as temperature, intensity and spectrum of the incident light.

Fill Factor (FF): Fill factor is defined as the ratio of photovoltaic actual power (P_{out}) to the theoretical power (P_T) if both the open circuit voltage and short circuit current were at their maximum. It is a measure of evaluating performance of the cell. Typical fill factors range from 0.5 to 0.82. Fill factor is often represented as a percentage.

$$FF = \frac{P_{max}}{P_T} = \frac{I_{mp} \cdot V_{mp}}{I_{sc} \cdot V_{oc}}$$

Figure 2. I-V curve of PV cell and associated electrical diagram



State of Current Solar Cells

The conventional Solar cells are made of semiconductor material, usually crystalline silicon (c-Si) as light absorbing semiconductor. It was developed in the 50s as first generation Solar cells. The first type of crystalline Solar cells is monocrystalline which are wafers, of about 0.3 mm thick, sawn from Si ingot of single crystal silicon made by using Czochralski process discovered in 1916. It is a method of crystal growth used to obtain single crystals of semiconductors, metals and salts with the most important application in the growth of large cylindrical ingots of single-crystal silicon. The ingots are typically 400 mm in diameter and 1 or 2m long. Dopants of n-type or p-types are added to make monojunction semiconductor device during the process.

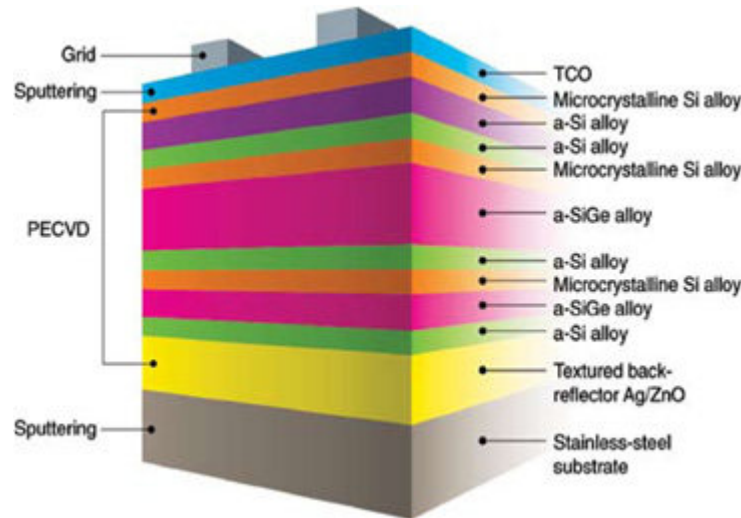
The second type of crystalline Solar cells are Polycrystalline (multicrystalline) made by sawing a cast square ingot block of silicon first into bars and then wafers. In this process molten multifacet crystalline silicon is first poured into a large molding container and carefully cooled and solidified. Polycrystalline Solar cells typically have a slightly lower efficiency of 13-15% resulting in larger individual cells and thus typically a slightly larger module ("Solar cell Technologies," n.d.). Monocrystalline cells are more expensive to manufacture and typically have a slightly higher efficiency of 13-18% than do conventional polycrystalline cells. Shockley and Queisser (1961) calculated the maximum thermodynamic efficiency for the conversion of unconcentrated irradiance into electrical free energy in the radiative limit to be 31%. This efficiency was obtained assuming a single threshold absorber and thermal equilibrium between electrons and photons. In this model excitation energy above the bandgap is lost to heating and excitation energy below the band gap is not absorbed. These cells are very efficient, approaching their theoretical efficiency in semiconductor with bandgaps ranging from about 1.25eV to 1.45 eV but are very expensive

due to the manufacturing processes used to make them. Solar radiation contains photons with energies from about 0.5 eV to 3.5 eV. Mass produced Solar cells are less efficient and achieve only 10% efficiency. In 2007, first generation Solar cells accounted for 89.6% of commercial production and it is thought that it will not be able to provide energy more cost effective than fossil fuel sources (Lenardic, 2008 & 2010).

To reduce the high cost of crystalline silicon which makes up to 40-50% of the cost of finished product led the industry to the second generation Solar cells based on thin film semiconductors developed in the 1990s and early 2000s. These cells are made with minimal materials of about 1 micron thick and can be deposited on a large area substrate of 1 meter using cheap manufacturing processes. The manufacturing materials include amorphous silicon (a-Si) or polycrystalline materials such as copper indium gallium diselenide (CIS or CIGS), and (CdTe) cadmium telluride (Ginley, Green, Collins, 2008). Amorphous silicon cells are typically single or triple junction designs laid down in multiple layers by vacuum deposition processes such as plasma enhanced chemical vapor deposition (PECVD) and sputtering as shown in Figure 3.

Amorphous silicon has a larger absorption coefficient because of quasi-direct bandgap and hence needs thinner absorbing layers and less material cost than crystalline silicon which absorbs less light near its band edge. Currently it has been the most commercially successful thin film photovoltaic technology with 5-6% of the total PV market. These cells with bandgap of ~ 1.7 eV can be doped in a fashion similar to c-Si, to form p-i-n-type semiconductor junctions and often used to produce large-area photovoltaic Solar cells. Amorphous silicon cells, however suffer from light induced instability that causes the cell efficiency to degrade with time. This effect is known as Staebler Wronski and was discovered by D. L. Staebler and Christopher R. Wronski in 1977 who showed that the dark conductivity and photocon-

Figure 3. Triple-junction spectrum-splitting amorphous (Si/Ge and Si) and microcrystalline silicon Solar cell structure (©2006, Yan et al.)



ductivity of hydrogenated amorphous silicon can be reduced significantly by prolonged illumination with intense light. Polycrystalline silicon (bandgap of 1.1 eV) consists solely of crystalline silicon grains (1mm), separated by grain boundaries. Their main advantage over amorphous Si is the mobility of the charge carriers. Polycrystalline material shows greater stability under electric field and light-induced stress. Cadmium telluride (CdTe) cells (band gap of ~ 1.58 eV) deposited on glass are usually sandwiched with cadmium sulfide (CdS) to form a heterojunction photovoltaic Solar cell. It is cheaper than silicon, especially in thin-film Solar cell technology but is less efficient. Copper indium gallium diselenide (CIGS) alloy cells (bandgap of ~ 1.38 eV) are deposited on either glass or stainless steel substrates but are more complex heterojunction models (Solar cell technologies, n.d., Lenardie, 2008, Ginley, Green & Collins, 2008).

Challenges of Photovoltaic Cell

Since the beginning of Solar cell development based on crystalline silicon, there have been efforts

to produce wafers directly from the melt instead of through crystallization of ingots. One of the methods is known as EFG (edge-defined film-fed-growth) which differs from the conventional method in that the thin silicon wafers are not sawn by wire saws from a block but are drawn directly as silicon film from a silicon furnace. To achieve this silicon film is produced in the form of an octagonal hollow pipe and pulled directly from the silicon melt. A laser is used to cut out the wafers from the surface shell of this hollow pipe. This process reduces the waste because only about 10% of the silicon material is cut away and recycled compared to Kerf losses (typically 50%) in the conventional wire sawing process and makes it lighter on resource use and more efficient than other processes. The first EFG ribbon was grown in 1971 by Tyco Labs and since the mid-1990s, the EFG technique has reached a mature and competitive status at RWE Schott Solar http://www.us.schott.com/photovoltaic/english/about_pv/technologies/crystalline2010.

The efficiency of silicon ribbon cells is in the range of 14 -16% which is less than monocrystalline photovoltaic cells.

Another method of making wafers for photovoltaic cells is based on String Ribbon which was proposed in 1980 by Emauel M. Sachs (“Building Solar cells”, 2007) and is used for making Solar cells by Evergreen Solar, Inc., (<http://evergreen-solar.com/en/>) since 1994. This method uses two high-temperature strings which are pulled vertically through a shallow crucible of molten silicon. As the string exits the silicon melt, a thin film is formed between the strings through surface tension. During this continuous process the thin film solidifies between the strings forming a silicon ribbon of long length out of the melt. The melt is replenished and silicon ribbon is cut into smaller pieces for further processing into Solar cells without interrupting growth. String Ribbon technology like EFG ribbons wafer offers a less expensive manufacturing technique but is not capable of achieving the same electrical performance as wafer technology. A traditional cut wafer will convert typically 15-16% of the incoming light into electricity where String Ribbon Solar cells are capable of converting 13-14%. Nakayashiki & Rounsaville et al. (2006) have obtained conversion efficiency as high as 18.3%, in the laboratory, however it cannot be produced commercially to this specification.

The two main drawbacks of the current semiconductor photovoltaic cells, the lower efficiency and higher cost, are inherent to single bandgap silicon semiconductor cells. Crystalline silicon has a bandgap energy of 1.1 eV. Photon energy of light varies according to the different wavelength of light and the entire spectrum of sunlight, from infrared to ultraviolet covering a range of about 0.5 eV to about 2.9 eV. A major factor limiting the conversion efficiency is due to large bandgaps for low energy to be absorbed, while much of the energy from electrons freed up by high-energy is lost as the electron is extracted. This results in creating charge carriers with a total excess kinetic energy equal to the difference between the photon energy and the bandgap. This excess kinetic energy is converted to heat as the photo-

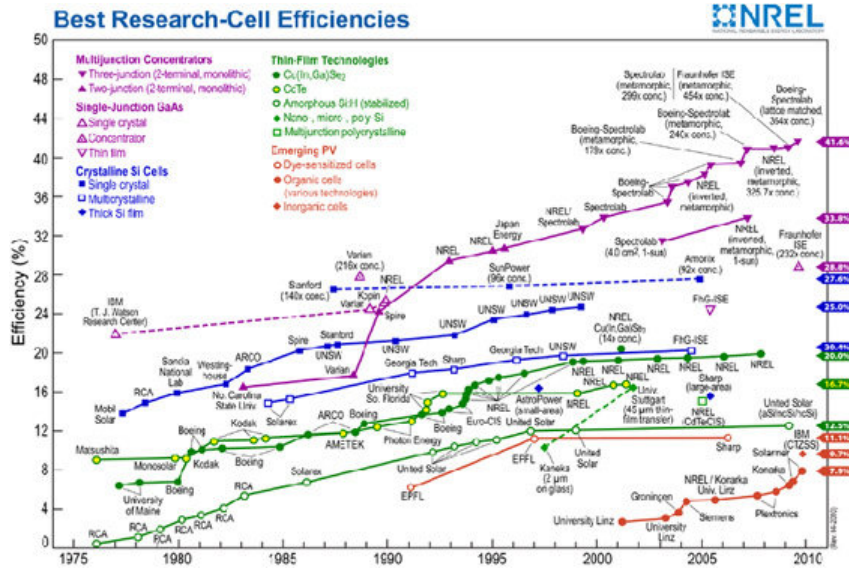
generated electron interacts with the vibrations of the semiconductor lattice called the phonons and cools to the bottom conduction band. At the most only 55% of sunlight energy can be used because either the energy is below the bandgap of the material or carries excess energy in most of the materials used in photovoltaic cell.

Surek (2005) studied the progress made in the last several decades for efficiencies of research scale photovoltaic devices including crystalline silicon, thin film, thin film and concentrators and the future generation photovoltaic cells as shown in Figure 4.

It is found that in nearly all the photovoltaic cell technologies conversion efficiencies increased because of better understanding of materials and device properties. Crystalline silicon based cell has already reached close to the theoretical thermodynamic limit of 31%. The efficiencies of thin film technology amorphous silicon, CIGS and CdTe, progressed steadily but are still below their full potential. The efficiencies of emerging dye cells, organic photovoltaic cells shown in Figure 4, are currently much lower and still being investigated. The production efficiencies of commercial or the best prototype modules are only 50-60% lower than the efficiency of best research cells.

The cost of crystal silicon which represents nearly 90% of solar panels has shown a decrease with the increase of production. The price has dropped by approximately 20% for every doubling of the total cumulative production of photovoltaic modules worldwide. The current cost of approximately \$4 per watt peak ($\$/W_p$) is still high to influence energy production markets. It is estimated, though difficult to determine, that costs for wafer-based silicon panels will level off in the range of \$1-1.5/ W_p in the next 10 years., which is still higher than 0.33\$/ W_p target (Margolis, 2003). Many of the emerging third generation technology based Solar cells including Gritzel cell, organic photovoltaic cells, quantum dot Solar cell and multiple exciton devices can be fabricated with low cost because they require

Figure 4. Progress of research-scale photovoltaic device efficiencies, under AM 1.5 simulated solar illumination for a variety of technologies (©2010 Kazmerski; Used with permission)



low temperature and low atmospheric pressure processing techniques such as spray painting or inkjet printing. These devices however are in the development stage with efficiencies in the range of around 10%, with the promise of exceeding efficiency beyond the Shockley-Queisser limit in certain cases (Ginley, Green, Collins, 2008).

NANOTECHNOLOGY BASED PHOTOVOLTAIC CELLS

In order to increase efficiency and reduce cost, research is targeted to third generation cells in the last few years, with respect to finding an effective alternative to silicon-based Solar cells. The goals of third generation Solar cell research are higher efficiency and lower cost per watt of electricity generated. In conventional photovoltaic cells photons with less energy than the band gap slip right through without being absorbed, while photons with energy higher than the band gap are absorbed, but their excess energy is wasted, and dissipated as heat. The maximum theoretical

efficiency that a Solar cell can achieve from a single material is about 31%, whereas in practice, the best achievable efficiency is about 25%. It is possible to improve on the efficiency by stacking materials with different band gaps together in multi-junction cells with dozens of different layers, by greater than 70 percent. However this method of achieving higher efficiency results in technical problems such as strain damages to the crystal layers. The most efficient multi-junction Solar cell consists of three layers: gallium indium phosphide/gallium arsenide/germanium (GaInP/GaAs/Ge) and is based on dual junction GaInP/GaAs Solar cell made in 2001 by the National Renewable Energy laboratory (NREL) in partnership with Spectrolab Inc., of USA. It was the first monolithic cell to reach a record of 34% efficiency under concentrated sunlight designed for terrestrial application. ("Material and Device Development," June 29, 2005).

Nanotechnology might be one of the emerging technologies to be able to increase the efficiency and reduce the cost of Solar cells. The third generation Solar cells tends to include, among others,

nonsemiconductor technologies (including polymer-based cells and biomimetics), quantum dot technologies, nanostructured cells using nanorods to better pick incident light, tandem/multi-junction cells, hot-carrier cells, dye-sensitized Solar cells and upconversion technologies. It is predicted that third generation cells could start to be commercialized sometime around 2020. Nanotechnology can be used to improve the efficiency and reduce the cost by making use of nanotechnology in the following way.

Improvement of Efficiency of Photovoltaic Cells by Quantum Dots

For improving the efficiency of photovoltaic cells beyond standard thermodynamic limit, quantum dots are used because of their unique properties. Quantum dots (QDs) are semiconductor nanocrystals of nanometers dimensions whose electrons-holes (excitons) are confined in all three spatial dimensions. Quantum dots have discrete electronic states, and the absorption of photons with energies greater than the energy difference between the highest hole state (1 Sh) and the lowest electron state (1 Se) (also termed the HOMO-LUMO transition) produces excited exciton. They have quantum optical properties that are not found in the bulk material due to the property of quantum confinement exhibited by the nanoscale structures. Quantum dots were discovered by Ekimov & Onushchenko (1981) in a glass matrix and by Louis E. Brus in colloidal solutions. The term quantum dot was coined by Mark Reed of Yale University.

The first advantage of quantum dots is its ability to change bandgap with the change in size of quantum dot so that the wavelength at which it will absorb or emit light can be adjusted to specific application. The bandgap increases as the size of quantum dot is reduced which in turn shortens the wavelength and shifts toward blue or ultraviolet light. On the contrary as the size of quantum dot is increased, the wavelength becomes longer and

shifts toward red light. This property of quantum dot is used in extending the bandgap of Solar cells and increasing the maximum proportion of incident light absorbed, hence improving efficiency.

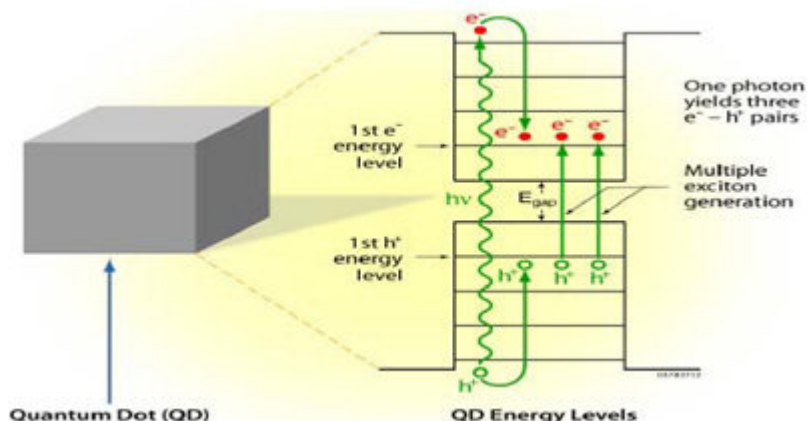
The second advantage of quantum dot in comparison to semiconductor crystalline structure used in other photovoltaic cell is its lack of rigidity which helps in constructing or molding it into different shapes including sheets or three dimensional arrays. Quantum dots prepared by colloidal synthesis are free floating in solution and can be easily made in porous films or combined with conductive or semiconductor polymers or dyes. Because of the possibility of using liquid phase, which requires relatively low temperature, it is possible to create junctions on inexpensive substrates such as coated glass, metal sheets and plastics (Mae-Wan, 2006). This approach does not need the costly microfabrication processes used to make contemporary silicon and thin-film based Solar cells.

Quantum Dots for Multiple Exciton Generation (MEG)

One of the methods of increasing the efficiency of Solar cells beyond the Shockley-Queisser limit is to utilize high efficiency carrier multiplication through multiple exciton generation which has recently been demonstrated in quantum dots. Multiple exciton generation involves the generation of more than one exciton from the absorption of a single photon as shown in figure 5.

It is based on impact ionization which produces multiple electron-hole pairs when a photon is absorbed in semiconductors that are at least twice the bandgap. The creation of multiple electron hole pairs in bulk materials has been known since 1960's for germanium and has been demonstrated in bulk silicon Solar cells (Kolodinski et al. 1993). The impact ionization effect in bulk materials is too small to be used for any substantial efficiency enhancement. In bulk semiconductors the phenomenon of multiple formations of

Figure 5. Multiple carrier generation solar cells. Utilization of high energy photon to multiple electron-hole pairs. (©2007, Nozik; Used with permission). Retrieved from http://www.nerl.gov_review/2007/Innovation_quantum.html



excitons does not occur as the excess energy of photons dissipates away in the form of heat before it can cause other electron-hole pairs to form. Whereas in semiconducting quantum dots the probability of charge carriers increases resulting in enhancements of exciton formation because the rate of energy dissipation is significantly reduced and charge carriers are confined. MEG has been recently demonstrated in synthesized nanocrystals (quantum dots) including PbS, PbSe, PbTe, CdS, CdSe, InAs, and Si (Kim, S.J., Kim, W. Jin., Sahoo, Y., Cartwright, A.N., & Prasad, P. N. 2008). MEG has also been demonstrated in InP colloidal quantum dots (Beard, MC., Knutsen, KP., Yu, P., Luther, JM., Song, Q. 2007). Quantum dots made of PbSe (2.9 nm diameter) and PbS has demonstrated the ability to achieve quantum efficiencies over 300% when the energy of photons absorbed is four times that of bandgap and multiple exciton start to form when the photon energy reaches twice the bandgap. In case of single-bandgap photovoltaic devices impact ionization produces greatly enhanced theoretical thermodynamic conversion efficiencies ranging from 45- to 85% depending on cell temperature, solar concentration and the number of electron-hole pairs produced per photon (Hanna, Ellingson, Beard, Yu, Micic, & Nozik, 2004)

Quantum Dots in Hot Carriers

Quantum dots have been used to increase the efficiency by capturing hot electrons which are lost as heat in solar-to-electric power conversion. Quantum dots in the form of semiconductor nanocrystals have been shown to slow down the cooling and increase the life time of hot electrons by as much as 1000 times (Tisdale, Williams, Timp, Norris & Aydil, 2010). The first prediction of slowed cooling at low light intensities in quantized structures was made by Boudreaux, Williams & Nozik (1980) who anticipated that cooling of carriers would require multi-phonon processes when the quantized levels are separated in energy by more than phonon energies. Hot carriers refer to electrons or holes that have gained very high kinetic energy after being accelerated by a strong electric field within a semiconductor such as MOS. Because of high electric field the carriers can be injected or trapped in certain unallowable areas of the semiconductor forming space charge. The influence of space charge shifts some of the characteristics of the device and can cause the device to degrade or become unstable (Hot carriers, 2004). In hot carrier Solar cell device electrons and holes, heated by incident photons by solar radiation are removed from the absorber

before the resultant hot carriers can thermalise with the lattice, and collect them in the external circuit.

Carrier thermalisation typically occurs in a few picoseconds; hence a significant slowing of carrier cooling is required which occurs due to the interaction with phonons in the semiconductor lattice. The hot carriers relax in a short time in the order of a few picoseconds by the emission of optical phonons and subsequent cooling to the band edge occurs via acoustic phonon scattering known as Klemens mechanism. This phenomenon of interference with optical to acoustic phonon scattering has the potential to significantly reduce carrier cooling rates. A periodic network of quantum structures, such as semiconductor nanoparticles, incorporated into the absorber material has been shown to significantly reduce the scattering between phonon modes effect called the phonon bottleneck. Conibeer, Green, Marti, Luque & Guillemoles (2008) implemented phonon bottleneck by engineering a nanoparticle network embedded in an absorber matrix that is homogeneous on a scale greater than a few tens of nanometers. Such a structure is compatible with thin-film deposition techniques and retains the potential for high efficiencies.

Quantum Dot Solar Cell Configurations

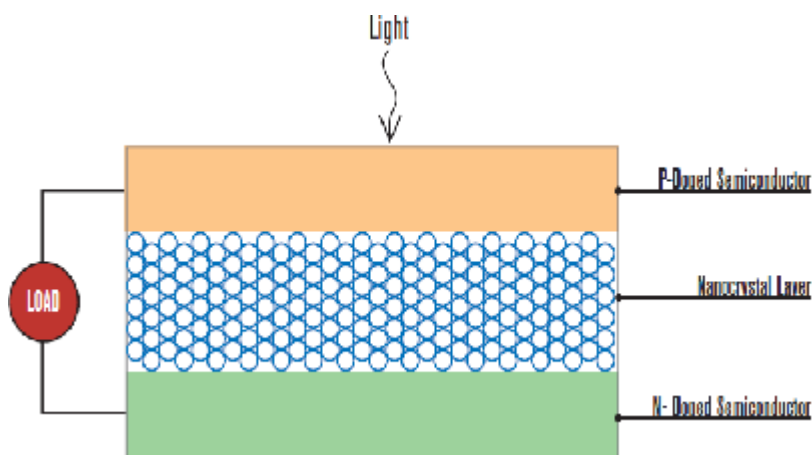
For enhancing the conversion efficiency of quantum dot Solar cell, Nozik (2001) proposed the following three conceptual configurations. These configurations are based on two fundamental pathways of increasing photovoltage (Ross and Nozik, 1982; Boudreaux, Williams, Nozik, 1980) and increasing photocurrent (Landsberg, Nussbaumer, Willeke, 1993; Kolodinski, Werner, Wittchen, and Queisser, 1993)

- Photodetectors composed of quantum dot arrays
- Quantum dot-sensitized nanocrystalline TiO_2 Solar cells
- Quantum dot dispersed in organic semiconductor polymer matrices

Photodetectors Composed of Quantum Dot Arrays: This configuration deals with three dimensional (3-D) array arrangement of quantum dots (nanocrystals) superlattices with sufficiently small spacing so that strong electronic coupling occurs and minibands are formed. It is a 3-D system similar to a 1-D superlattice and the nanocrystal array is placed in the intrinsic region of a p-i-n structure as shown in figure 6.

The formation of a delocalized quantized 3-D miniband formed as a result of three dimensional ordering of closely spaced quantum dots allows long range electron transport leading to high values of carrier mobility required in infrared photodetectors. Delocation state is a state of motion in which a charge carrier is spread over a whole molecule or crystal. These quantized states could also be expected to slow the carrier cooling and permit the transport and collection of hot carriers at respective p- and n- contacts to produce a higher photopotential in a Photovoltaic cell or in a photoelectrochemical cell in which 3-D nanocrystal array is the photoelectrode. The phenomena of MEG and hot electron transport / collection however cannot take place simultaneously and only one of the two processes can be present in a given system. Although fabrication of 3-D ordered quantum dots is still a major problem, significant progress has been made in forming 3-D arrays of both colloidal and epitaxial II-VI and III-V quantum dots. The colloidal quantum dots have been formed via evaporation and crystallization of colloidal QD solutions containing a uniform QD size distribution. The crystallization of QD solids from broader size distributions leads to close-packed QD solids, but with a high degree of disorder. In the epitaxial II-VI and III-V, process QDs have been formed by successive epitaxial deposition of QD layers. Once the first layer of QDs is formed, successive layers tend to form with the QDs in each layer aligned on top of each other (Nozik, 2006). The epitaxial self-assembled QDs are commonly obtained by the Stranski-Krastanow (SK) growth mode, which follows a two step process in which

Figure 6. Quantum dot arrays solar cell



QDs forms on top of a thin two-dimensional wetting layer. This process is also known as ‘layer –plus island growth,’ the properties of the wetting layer such as thickness and composition are hard to control independently of those of the overlying QDs.

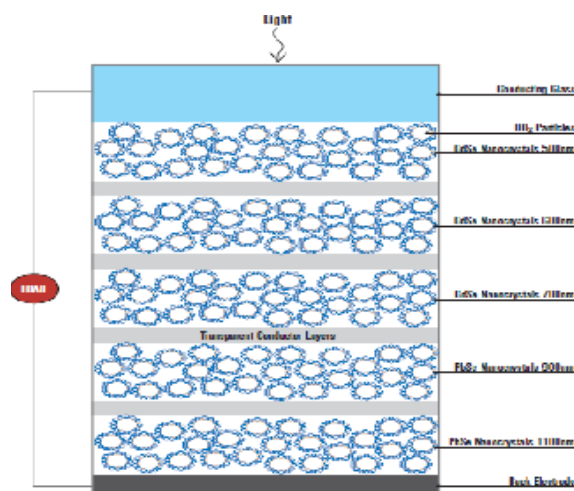
Quantum Dot-sensitized Nanocrystalline TiO₂ Solar cells: Quantum dot-sensitized nanocrystalline TiO₂ Solar cells configuration is a variation of a relatively new type of photovoltaic cell based on dye-sensitized Solar cells (DSSC) was invented by Gratzel and O’Regan (1991). DSSC consists of photoelectric structures composed of mesoporous oxide layers of nanocrystalline TiO₂ which have been sintered together to allow for electronic conduction to take place. The commonly used oxide TiO₂ is a thick semiconductor nanoparticle film which acts as an electrode that provides a large surface area for the adsorption of light harvesting organic dye molecules. This porous electrode absorbs light in the visible region of electromagnetic spectrum and then initiates the charge separation process eventually leading to the generation of photocurrent. The process is accompanied by a charge transfer to the dye from an electron donor mediator supplied by an electrolyte, hence resetting the cycle. One of the problems with this cell is that only a few

dyes can absorb a broad spectral range covering solar spectrum. The high efficiency of these cells is contributed to the fact that the mesoporous TiO₂ nanoparticles increase the surface area for dye chemisorptions to a thousand times over a flat electrode of the same size. One of the main reasons of slow progress is due to the limited diffusion length of photogenerated electrons which conducts by way of random hopping through a percolated path in a three dimensional network of TiO₂ nanoparticles. One of the approaches to improve the electron transport is to replace TiO₂ nanoparticles with crystalline TiO₂ nanorods or nanowires.

In quantum dot –sensitized cells as shown in Figure 7, dye molecules are replaced by quantum dots which have been successfully implanted using semiconductor quantum dots including CdS, CdSe, InP, and PbS (Zaban, Micic, Gregg, Nozik. Langmuir, 1998; Vogel and Weller, 1994; Weller and Bunsen-Ges, 1991; Liu & Kamat, 1993; Hoyer & Konekamp, 1995).

Advantages of using quantum dots over dye molecules include tunability of optical properties with size and capability of producing greater quantum yield than impact ionization. Despite advantages of dye sensitized Solar cells, they suffer from electrolyte leakage.

Figure 7. Quantum dot –sensitized solar cell



Quantum dot Dispersed In Organic Semiconductor Polymer Matrices: Photovoltaic effect is found in structures composed of quantum dots forming junctions with organic conjugate polymers. Conjugate polymers are organic polymers which conduct electricity and may either be semiconductors or metallic conductors. These polymers are also plastics which can combine mechanical properties of plastics such as toughness, flexibility, elasticity etc; with the electrical conductivities. Conjugate photovoltaics offer a low cost, easily manufactured and non-toxic alternative to in-organic based Solar cells. However for many conjugated polymers, charge-carrier mobility is usually limited by disorder effect, which prevents inter-chain coupling. In order to improve the electronic mobility, polymer photovoltaic devices rely on the introduction of another material which also provides an interface for charge transport. High efficiency can be achieved by forming a photovoltaic cell by blending conjugate polymers with CdSe nanocrystal as shown in figure 8.

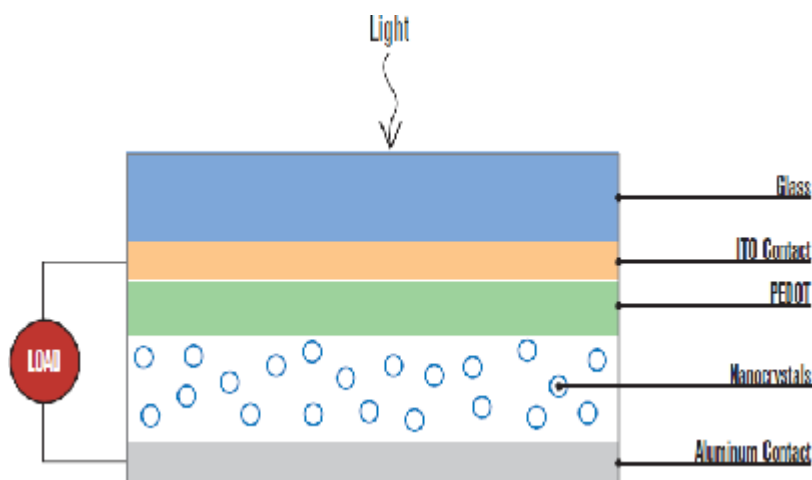
The advantage of using CdSe nanocrystals is to have two components in the bulk heterojunction that can absorb visible light and contribute to photocurrent. Another advantage of using CdSe nanocrystal lies in the shape of the CdSe nano-

crystal which can be controlled to give highly elongated molecules, resulting in better pathways for electron transport. Greenham et al (1996) first reported the photo luminescence quenching in MEH-PPV (poly (2-methoxy, 5-(2'-ethyl)-hexyloxy-p-phenylenevinylene) by intermixing it with the spherical nanoparticles (quantum dots) of 5 nm diameter of CdS and CdSe. In this configuration disordered array of CdSe quantum dots is electron conducting material and MEH-PPV is a hole conducting conjugate polymer. The photo-generated holes produced as a result of photo-excitation of the quantum dots are injected into the MEH-PPV polymer phase, and are collected via electrical contacts to the polymer phase. The electrons on the other hand remain in the CdSe quantum dots and are collected through diffusion and percolation in the nanocrystalline phase to an electrical contact to the quantum dot network (Greenham, Peng, Alivisatos, 1996; Greenham, Peng, and Alivisatos, 1997). The quantum efficiency (EQE) of conjugated Polymer–CdSe nanocrystal photovoltaic cell made by depositing the blended films on a transparent indium –tin oxide (ITO) electrode and using an evaporated aluminum top electrode was 12% under low intensity light. The power efficiency under AM 1.5 G conditions was estimated to be around 0.1%. The performance of the photovoltaic cell improved by increasing the weight fraction of nanocrystal, leading to the conclusion that low efficiency is the result of poor electron transport in photovoltaic conversion.

Nanorods Based Solar Cells

One way of improving the efficiency of quantum dot conjugated polymer Solar cell is to use one dimensional nanorod which provides a directed path for electrical transport. Nanorods are also used to control the bandgap by varying the radius of rods and using the quantum size effect. Using quantum confinement effect the absorption coefficient of

Figure 8. Quantum dot blended conjugate polymer solar cell



nanorods can be enhanced which will affect the length and width of nanorods leading to thinner devices for optimal absorption of incident light. Huynh et al. (2002) combined nanorods CdSe with the conjugated polymer poly-3 (hexylthiophene) (P3HT) to create charge transfer junctions with high interfacial area. CdSe nanocrystal in this combination as shown in Figure 9, is used as electron transport material while P3HT is used as effective hole transport material.

The photovoltaic device consisting of 7 nm x 60 nm CdSe nanorods and P3HT was assembled using solution phase synthesis at temperature below 300° C. External quantum efficiency of over 54% and monochromatic power conversion of 6.9% was obtained under 0.1 mW per square cm illumination at 515 nm. The device showed a short circuit current of 5.7 mA, open circuit voltage of 0.7 V, a fill factor of 0.4, and a power conversion efficiency of 1.7% was under Air Mass (AM) of 1.5. Bandgap tuning by varying the nanorod radius was used to optimize the overlap between the absorption spectrum of the cell and the solar emission spectrum of the sun leading to improved optical absorption in the visible range.

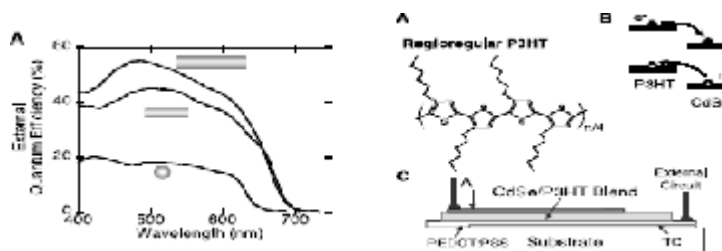
In another configuration, Arango et al. (1999) made the first polycrystalline TiO_2 -polymer photovoltaic cell by sintering together TiO_2

nanocrystals and then spin casting MEH-PPV on top. TiO_2 layer is used as electron conducting phase and MEH-PPV is used as hole conducting phase and a gold top electrode was used to extract holes from polymer. External quantum at the peak absorption wavelength of the polymer was found to be 2% and 6% for the devices with solid and nanoporous TiO_2 respectively. TiO_2 , although absorbs less visible light than CdSe, has advantage of being better electron-accepting material than CdSe.

Nanotube Based Solar Cells

Because of low carrier mobility and inefficient charge transfer in majority of polymers cells including CdSe quantum dots and semiconductor nanorods, the use of carbon nanotubes in these devices is an attractive approach for several reasons. Single wall nanotubes (SWNTs) have a nanometer-scale diameter and exhibit ballistic electrical conductivity and are very efficient for transporting electrons and providing high electric field at the polymer/nanotube interfaces. This coupled with extremely high surface area for purified SWCNT provides a tremendous opportunity for exciton dissociation. SWCNT exhibit large aspect ratio and at low doping levels percolation

Figure 9. Hybrid nanorod polymer solar cell (©2011; Huynh, et al., Used with permission)



pathways are established providing the means for a higher carrier mobility and efficient charge transfer. In addition SWCNT offers unique properties of offering a wide range of bandgaps to match the solar spectrum, enhanced optical absorption and reduced carrier scattering for hot carrier transport.

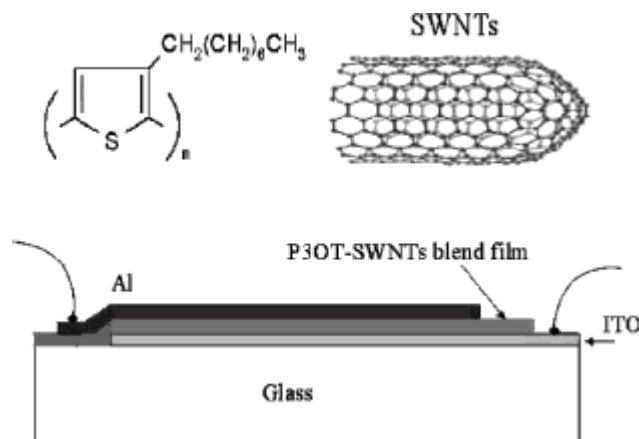
The motivation for investigating the use of carbon nanotube as an electronic transport material in polymer cells started after the discovery in 1992 of photoinduced charge transfer between conjugated polymers and buckminsterfullerene and its derivatives. Buckminsterfullerene, C_{60} is the smallest fullerene molecule made up of 60 carbon atoms arranged in a series of interlocking hexagons and pentagons, forming a structure that looks similar to a soccer ball. It is the third allotrope of Carbon, which was discovered in 1985 by Robert Curl, Harold Kroto and Richard Smalley. Carbon nanotubes are allotropes of carbon with a cylindrical structure. Carbon nanotubes were discovered by Sumio Iijima in 1991. They are members of fullerene structural family and were produced by vaporizing carbon graphite with an electric arc under an inert atmosphere. A nanotube is not a metal, but a structure built by covalent bonds whereas SWCNT is a graphite sheet that is rolled into a cylinder of a few micrometres in length and a few nanometers in diameter. In single walled carbon nanotubes (SWNTs), the small Fermi velocity and low dielectric constant suggests that electron-electron interactions are very strong and that high-energy carriers should efficiently generate e-h pairs.

Nanotube in Organic (Polymer) Cell

The dispersion of SWNTs into polymers like poly (3-octylthiophene) - (P3OT) has been shown to dramatically improve both the electrical conductivity and optical absorption of the polymer in comparison to the pure polymer. The photoresponse of Solar cells using P3OT doped with SWNTs is significantly improved over the undoped version under simulated air mass zero (AM0) illumination. The use of CNTs as electron acceptors in bulk-heterojunction Solar cells was first reported in 2002 by Emmanuel Kymaki et al (2002). The author integrated single-walled carbon nanotubes (SWNTs) in conjugated electron transfer at the polymer/nanotube interface and observed an increase in the photocurrent of two orders of magnitude. The device shown in Figure 10, composed of a sandwich formation containing the composite film between an indium –tin-oxide (ITO) front and aluminum back as showed a diode response.

The SWNT used was synthesized using arc discharge method. The purity of SWCNT powder was estimated to be about 60% which was self organized into 1.4 nm of bundle-like crystallinities and carbon encased nanoparticles. A chloroform solution was used to dissolve nanotube powder which was then dispersed using high power ultrasonic probe and blended with P3OT solution for 1 hour sonication. Organic films were developed from chloroforms solution by drop and spin coating onto a glass substrate with ITO. Electrodes

Figure 10. Chemical structure of P3OT, SWNTs, and device structure of the photovoltaic cell (©2002, Kymakis & Amaratunga; Used with permission)



of aluminum were thermally evaporated under a vacuum. Both the pristine device ITO/P3OT/Al and blended devices 1% ITO/P3OT-SWNTs/blend devices were tested under dark and white light illumination (AM 1.5, 100 mW/cm²) from the glass/ITO side and showed that the dark current is much higher in forward bias than in reverse bias indicating diode behavior. The 1% doped by weight blend of SWCNT/P3OT under illumination showed short circuit photocurrent density of 0.12 mA/cm² and an open circuit voltage of 0.75 V, compared to 0.7 uA/cm² and 0.35 V for pristine P3OT devices (Kymakis and Amaratunga, 2002 ; Kymakis, Kornilios and Koudoumas, 2008). Lee Ji U (2005) demonstrated that carbon nanotubes can form ideal p-n junction diodes and observed a photovoltaic effect in a pristine nanotube diode device consisting of two CNTs with different electrical properties. Under illumination, SWNT diodes show significant power conversion efficiencies owing to enhanced properties of an ideal diode.

Bailey et al. (2005) investigated light weight flexible photovoltaic devices based on regioregular P3OT/SWCNT for space power applications. The devices were constructed by blending regioregular poly(3-octylthiophene) with 1% by weight of single wall carbon nanotubes purified more than

95% by weight. The nanotubes were synthesized by using pulse laser vaporization technique which employed Alexandrite laser of 755 nm to target the surface of Ni/Co doped graphite. The preparation of a SWNT-P3OT composite was achieved by a series of steps starting first by dissolving regioregular P3OT in chloroform using water bath sonication to achieve pristine solution. Next, the composite dispersion was performed by blending purified SWCNTs to the pristine solution at the desired doping levels. The composite solution was then placed in a water bath sonicator for five minutes before stirring it at high speed for 72 hours at room temperature. Portion of dispensed solution was cast on Teflon substrate to produce desired thin films at room temperature. Device fabrication involved deposition of P3OT composite on ITO –coated polyethylene terephthalate. This is achieved initially by spray depositing an intrinsic layer of pristine P3OT on to a masked active area of the substrate followed by spray deposition of the SWCNT-P3OT composite solution. This approach of deposition has the advantage of making thin film polycrystalline Solar cells more flexible and lower in structural weight. The Solar cells are eventually completed by applying aluminum contacts using thermal evaporation under vacuum to the SWNT –P3OT and ITO composite film layers.

The polymer Solar cells used a stable composite dispersion of 0.1% by weight SWNT for pristine P3OT and 1.0% by weight SWNT in P3OT. It was tested under simulated AM0 illumination for I-V characterization and showed photoresponse with an open circuit voltage of 0.98 V and short circuit current density of 0.12 mA/cm². The result also showed that there is an apparent conductivity effect on short circuit current in the composite films which can be controlled by SWNT doping.

Mitra & Li (2008) developed an organic photovoltaic cell by combining spherical fullerene C₆₀ with cylindrical SWCNT to improve quantum efficiency. C₆₀-SWCNT complex is fabricated on flexible plastic substrate as shown in Figure 11.

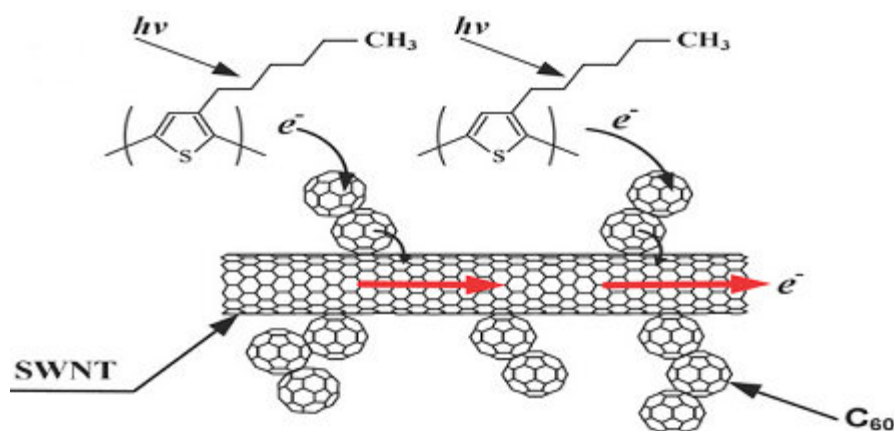
In this configuration C₆₀ was used to separate the photogenerated carriers because of its large surface –to- volume ratio, whereas SWCNT is used to efficiently transport the carrier because of its ballistic electrical conductivity that serve as tiny wires. To improve the performance of the photovoltaic cell SWCNT was added to a photoactive coating composed of poly (3-hexylthiophene). The short circuit current and fill factor improved significantly after introducing SWCNT into the photoactive composite layer via binding with C₆₀. Power conversion efficiency was improved by 78%.

Nanotube in Dye Sensitized Solar Cell

Despite many advantages of DSSC in cost efficiency compared to semiconductor Solar cell it suffers from temperature stability problem because of the use of the liquid electrolyte. The electrolyte can freeze at low temperature, ending power production and potentially leading to physical damage whereas at high temperature the electrolyte liquid can expand, making sealing a serious problem. In addition solvents used in the electrolyte permeate plastics, making large-scale outdoor application and integration into flexible structure more difficult.

Carbon nanotubes being transparent, easy to conduct electricity and good catalyst of electricity production can create a single layer that performs the functions of both the oxide used to conduct electricity and the platinum film to act as a catalyst to speed up the chemical reaction in dye-sensitized Solar cells. The oxide films used in DSSC has the disadvantage of not being applied to flexible materials which makes it expensive and limited in product application because of its suitability to a rigid and heat resistant substrate like glass. On the other hand carbon nanotube films are much more flexible, difficult to crack and are more suited to inexpensive roll-to-roll processing. Compared

Figure 11. Fullerene combined with SWCNT organic photovoltaic cell; (©2011, Mitra & Li; Used with permission)



to carbon nanotube platinum degrades easily over time when it makes contact with an iodide/tri-iodide liquid electrolyte, therefore reducing the efficiency. It has also been demonstrated that the conductivity and transparency of nanotube film has reached closer to transparent conducting oxide on rigid comparable to TCO on flexible substrate.

Trancik et al. (2008) used ozone treated carbon nanotube film as catalyst which showed high performance to replace platinum and a TCO in the DSSC. The films were deposited from single wall carbon nanotube which was produced using arc discharge method. The conductivity and transparency of carbon nanotube was also improved by increasing the length of carbon nanotube.

Single Wall Carbon Nanotube as Conducting Scaffold

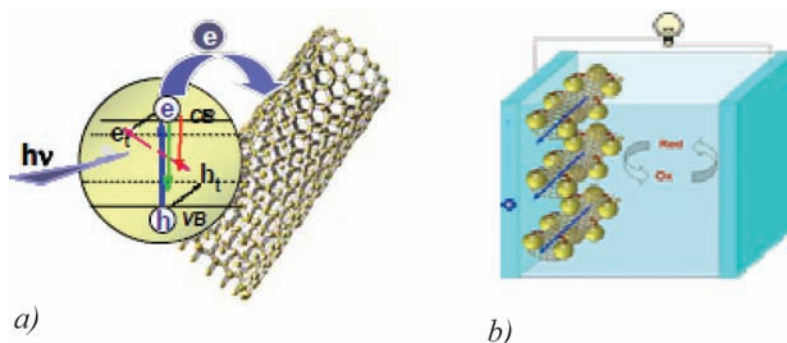
To improve the photoelectromechanical performance of photovoltaic cell based on semiconductor nanoparticles, SWCNT are also used as conducting scaffold. This is achieved by employing the unique properties of SWCNT namely the high surface area and wide electrochemical window to act as scaffold to anchor light gathering semiconductor particles. The performance can be improved in two ways. The first way is by separating the photoinduced charge in the attached semiconduc-

tor nanoparticles and the second is by aiding in collecting and transporting photogenerated charge carriers to the collecting electrode surface. The principle of such a process for a semiconductor particle–CNT based composite in the operation of photoelectrochemical cell is shown in Figure 12.

Kongkannad & Kamat et al. (2007) observed a twofold increase of photoconversion efficiency by creating SWCNT networks to disperse photo-active TiO_2 semiconductor nanoparticles. The SWCNT network was created on a conducting carbon fiber and glass electrodes where SWCNTs was used as a conducting scaffold to facilitate charge collection and charge transport in nanostructured semiconductor films.

This technique of light harvesting has also been used to improve the performance of DSSC which uses nanostructured TiO_2 films for transportation of electrons. The disadvantage of using nanostructured titanium dioxide in DSSC is that the photogenerated electrons have to travel through the network of semiconductor particles and encounter many grain boundaries, hence increasing the probability of recombination during random transit. Use of one dimension nanostructure such as TiO_2 and ZnO nanowires and nanotube, it is possible to direct the flow of photogenerated charge carriers and increase the photoconversion efficiency.

Figure 12. (a) Photoinduced charge injection from excited semiconductor particle into SWCNT and (b) SWCNT as conducting scaffold to transport photo-generated charge carriers in a photoelectrochemical cell (©2007, Kamat et al., Reproduced by permission of ECS-The Electrochemical Society)



Carbon Nanotube for Multiple Electron-Hole Pairs

Carbon nanotubes are shown to produce multiple electron-hole pairs in response to a single photon increasing photovoltaic efficiency beyond Shockley and Queisser of 31%. McEuen & et al. (2009) demonstrated this making photovoltaic cell of single wall carbon nanotube measuring 3–4 micrometer long and 1.5–3.6 nm in diameter as shown in Figure 13.

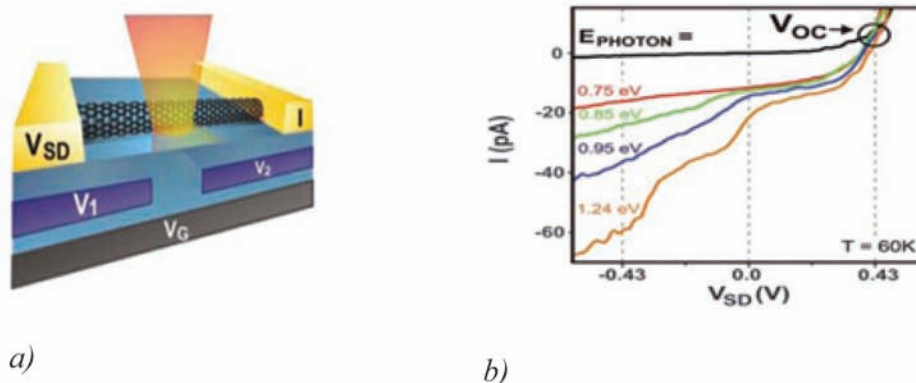
An insulating substrate is used to hold the carbon nanotube which also contains three buried electrodes. The nanotube behaves like a p-n junction photodiode when connected to appropriate voltages. A laser was used to illuminate the photodiode and monitor the changes in the current when an additional bias voltage was applied along the nanotube. Generation of multiple carriers was observed when voltages to the photodiode in opposite direction to freely flowing current were applied at or below 90K. The resulting current in response to light increased in steps as the voltage was increased. It is believed that generation of multiple electron hole pair is achieved by incident photons that increase the resulting electrons by more than one subband energy level. This second

band carrier gains enough energy to excite additional electrons by combining with photons excess energy which converts single electron in to extra electrons. In other words in SWCNT photodiode, a single photon with energy greater than twice of bandgap is converted into multiple electron-hole pairs leading to enhanced photocurrent and increased photo-conversion efficiency. This device however has to overcome the problem of scalability and investigation of efficiency mechanism at room temperature.

USE OF GRAPHENE IN SOLAR CELLS

Despite many advantages of nanotubes there are significant problems in the implementation on a large scale. The epitaxial graphene, on the other hand, avoids these problems while retaining many of the important electronic properties of carbon nanotubes. Recent work shows that graphene is highly conductive and highly transparent form of carbon which is a critical requirement for organic photovoltaic cell. It also shows outstanding thermal and chemical stability. One of the most important advantage of graphene based organic

Figure 13. (a) Experimental setup of a SWCNT photovoltaic cell (b) I-VSD characteristics of photovoltaic cell, (©2009, McEuen et al., Used with permission) Retrieved from <http://physicsworld.com/cws/article/news/40332>



Solar cell over the ITO is its physical flexibility which is commonly used as a transparent conductive through which light couples in or out of photovoltaic cell. ITO and other metal oxides are brittle and cannot be used on flexible substrates. Other problems of ITO as a conductive electrode include instability of metal oxides used in the presence of acid or base, susceptibility to ion diffusion in to polymer layers and limited transparency in the near –infrared region. Graphene is capable of absorbing a wide range of light frequencies compared to semiconductors, which typically need to be layered together for this purpose.

Graphene is basically a single layer of graphite, consisting of a hexagonal array of sp^2 -bonded carbon atoms, just like those found in bulk graphite. Although the existence of graphene has been known for decades, it was first discovered in its form of isolated thin carbon sheets (Novoselov et al, 2004). It is produced mostly by exfoliating graphite and is limited to small size, although the researchers have been working to produce large swaths of the ultrathin membrane since its discovery. Although graphene shows promise as an effective, relatively inexpensive, and less toxic alternative to other materials currently used in Solar cells, there are problems with graphene. The intrinsic graphene is a semi-metal or does not have a bandgap that is essential for semiconductor device operation. In the application of using attached grapheme films, large graphene sheets tend to clump together and there is a need to address issue of materials integration (Geim & Novoselov, 2007; Geim 2009).

Methods of Manufacturing Graphene

There are essentially four different methods of making graphene (Park, Ruoff, 2009). The first method started in 1970 used chemical vapor deposition of hydrocarbons on the surface of transition metals like nickel and subsequent transfer onto insulating substrates. This method has produced large area graphene films of single-to-few –layer

graphene on metal substrates, but lacks the sufficient structural homogeneity on large areas.

The second method deals with micromechanical exfoliation of graphite which was used first to isolate separate graphene in 2004. This method, called “Scotch Tape method” is based on mechanical exfoliation of graphite which is achieved by mounting flakes of highly ordered pyrolytic graphite (HOPG) on sticky tape and separating a single layer by carefully peeling away the tape which is essentially a stack of graphene sheets. This process is not easy as the individual sheets tend to clump together and graphite does not have the high mechanical strength because it is soft and flaky. It is not suitable for large-scale application.

The third method is based on epitaxial growth in which graphite layers are grown on top of other crystals which remain bound to underlying substrate like copper, nickel or silicon. The substrate is subsequently removed by chemical etching after the epitaxial structure is cooled down. It provides high quality multilayer grapheme samples interacting strongly with their substrates. However the ultra vacuum required makes its applications limited.

The fourth method is based on chemical exfoliation of graphite in which graphene is produced from colloidal suspensions made from graphite derivatives such as graphite oxide and graphite intercalation compounds (Park & Ruoff, 2009).

Large Area Graphite Oxide for Solar Cells

The commonly used method of making graphite oxide is Hummer method (Hummers Jr., & Offeman, 1958) in which graphite oxide is typically made by treating crystalline graphite with Sulfuric acid (H_2SO_4), Sodium nitrate ($NaNO_3$) and Potassium permanganate ($KMnO_4$) for overnight reaction, then mixing with water for further reaction, and finally rinsing with methanol. The oxidation product like the graphite consists of layered structure of graphene oxide sheets with

–OH and >O functionality so that intercalation of water molecules between the layers readily occurs. In other words graphite oxide is hydrophilic and readily disperses in water to form stable colloidal suspensions. Exfoliation of graphite oxide for producing aqueous colloidal suspension can be achieved by simple sonication and by stirring the water/graphite oxide mixture for a considerable time. This method of making grapheme is scalable and can be used for high volume production with the possibility of using it in many applications. It is also well suited to chemical functionalization.

Ruoff et al in 2008 showed that adding acid to graphite in water can yield graphite oxide that can be separated into individual pieces. The flakes which are suspended in liquid are then deposited onto a substrate to form a film. The addition of other chemicals or heat can drive off the oxygen groups, yielding graphene.

Although chemical exfoliation methods for making large size graphene are efficient, the process of oxidation introduces defects in as-made sheets. It has been shown to partially restore the structure and conductance of graphite oxide by making use of Hydrazine reaction at temperature below 100°C. This process however shows strong defect peaks and 2-3 order of magnitude higher resistivities than pristine grapheme. Hailiang et al (2009) used mild exfoliation–reintercalation expansion method for forming high-quality graphite sheet with higher conductivity and lower degree of oxidation than graphite oxide. This was achieved by using 180°C solvothermal reduction methods both for graphite sheets and graphite oxide. Solvothermal process is defined as a chemical reaction in which process is carried out in a thick walled steel vessel (autoclave) at higher temperature than boiling point of solvent and elevated pressure in the presence of nonaqueous solvent. This process is an extension of hypothermal method and solvothermal reduction is more effective than the earlier reduction methods in lowering the oxygen and defect levels in graphite sheets. Graphite sheets Oleum and tetrabutylammonium

cations were introduced in the graphite sheets made from graphite flakes and suspended in N, N-dimethylformamide (DMF). The reduction was carried in DMF at 180°C using solvothermal process and hydrazine monohydrate as the reducing agent. Graphite sheet of average size of about 300 nm on the side remained well dispersed in DMF after reduction. The height of graphene sheet (GS) used was between 0.8 to 1 nm.

Marcano et al (2010) improved the preparation of graphite oxide by excluding NaNO_3 and increasing the amount of KMnO_4 from the commonly used Hummers' method and performing the reaction in a 9:1 mixture of $\text{H}_2\text{SO}_4/\text{H}_3\text{PO}_4$. This method improved the efficiency of the oxidation process and provides greater amount of hydrophilic oxidized graphene compared to Hummers method with additional KMnO_4 . Hydrazine was used for reduction. This improved method does not generate toxic gas, is easy to control temperature and can be used for large scale production of graphite oxide film.

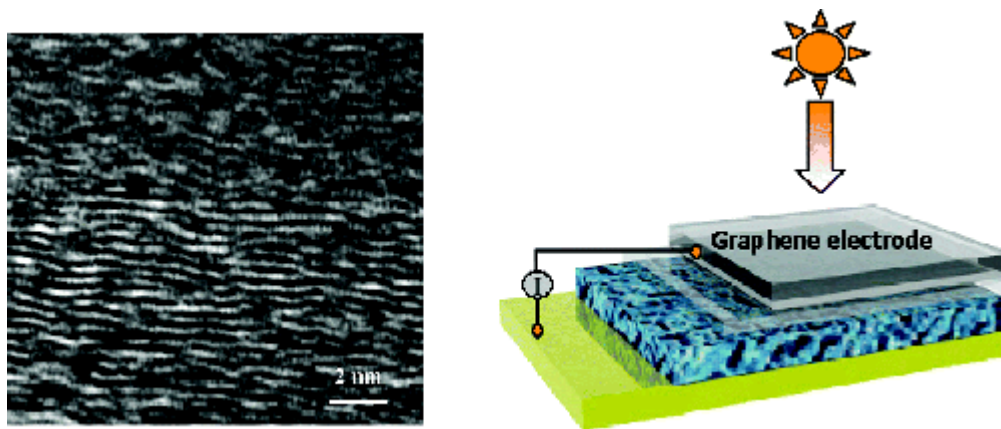
Graphene Based Solar Cells

Because of the advantages of graphene listed above, it has been used in dye-sensitized Solar cells (Wang, Zhi, and Mullen, 2008) and organic Solar cell (Wu, Becerril, Bao, Liu, Chen, Peumans, 2008; Gomez De Arco, Zhang, Schlenker, Ryu, Thompson, Zhou, 2010), as an anode to replace ITO.

Wang, Zhi & Mullen (2008) in 2007 demonstrated the application of graphene films by fabricating solid state dye sensitized Solar cells using graphene film as anode and gold as cathode as shown in Figure 14.

The anode consisted of organic molecule named spiro-OMeTAD (chemical name: 2,2',7,7'-tetrakis (*N*, *N*-di-*p* methoxyphenylamine)-9,9'-spiro-bifluorene) as a hole transport material and porous TiO_2 for electron transport. This is a solid state hole transport material which is most widely used in solid state DSSCs to over-

Figure 14. (a) High-resolution image of graphene films, (b) Illustration of dye-sensitized solar cell using graphene film, Au, and compact TiO₂, (©2008, Wang, Zhi, & Mullen)



come the problem of potential leakage and corrosion occurring in liquid based DSSCs. The I-V (current-voltage) characteristics of the photovoltaic cell under illumination of simulated solar light showed a short-circuit photocurrent density of 1.01 mA/cm², with an open circuit voltage of 0.7 V. The overall power conversion efficiency of 0.26% and calculated fill factor of 0.36 was obtained.

Graphene films as an alternative to metal oxide window electrodes for Solar cell were fabricated using Hummers method through acid oxidation of flake graphite. This was achieved first by depositing graphite oxide on pretreated substrates by way of dip coating of a hot dispersion of graphite oxide in water and then drying it by controlling the temperature. The thickness of the film was adjusted by changing the temperature of graphite oxide and number of time it is dipped. Reduction of graphite oxide was obtained by thermal treatment under protection of Ar and/or H₂ flow. This process resulted in graphite film of a thickness of a ca. 10nm which showed a high conductivity of 550 S/cm and transparency of more than 70% over 1000-3000 nm.

Wu et al. (2008) demonstrated the use of solution processed grapheme thin films as a transparent conductive anode for organic photovoltaic cell.

The graphene electrodes were deposited on quartz substrates by spin coating of functionalized graphene using modified Hummers method. This was achieved first by chemically oxidizing a graphite crystal by treating it with a solution of NaNO₃, KMnO₄, concentrated H₂SO₄ and 30 wt % H₂O₂, and washing with HCL and purified water. The resulting graphene sheets are then ultrasonicated to exfoliate the individual sheets producing a loose brown powder that can be separated. The spin coating rate is gradually increased first to spread the water dispersion on the quartz, and then drying the graphite film. The residual water is removed by heating graphite films to 100° C for several hours in a vacuum oven. In order to obtain acceptable sheets resistance the resulting functionalized graphene films must be reduced which partially restores electron decolonization and increases both the electrical conductivity and light absorption of the film. Small molecular organic photovoltaic cells were fabricated directly on quartz with thickness of grapheme films measuring 4 and 7 nm. The corresponding values of transmittance are between 85%-95% and sheet resistance between 100 to 500 Kilo ohms/sq. The short circuit current density, open circuit voltage, fill factor and power conversion efficiency of 2.1 mA/cm², 0.47 V and 0.34 respectively. The lower

short circuit current and fill factor of the graphene cell is caused by the high sheet resistance of the graphene thin films.

De Arco et al. (2010) created dense arrays of flexible organic photovoltaic cells by producing graphene/polymer sheets ranging in sizes up to 150 sq cm using chemical vapor deposition technology. This was achieved by first creating ultra thin graphene sheets by depositing carbon atoms in the form of graphene films on a nickel plate from methane gas. A protective layer of thermoplastic was then laid down over the graphene layer and dissolving the nickel underneath in a bath of acid. Finally the plastic protected graphene was attached to a very flexible polymer sheet which can be incorporated into a photovoltaic cell. The resultant Solar cells produced by this method are more flexible than those based on ITO, but less efficient. The reduced efficiency is compensated by the low price and ease of manufacturing. Because of its physical flexibility it could be hung as curtains or made into fabrics and be worn as power generating clothing. It was shown that compared to ITO graphene based cell remained operational after repeated bending at much larger stress angles.

CONCLUSION

Despite the immense potential of solar energy, it presents many challenges as the world's major alternative energy source. The widely used photovoltaic cells based on single bandgap semiconductors are costly and are limited by 31% efficiency set by Shockley and Queisser effect. The high price of Solar cells, around 90% of which uses crystal silicon is largely due to the use of expensive substrate materials and costly microfabrication processing. Although the cost has decreased with the increase of production, it is still high enough to influence energy production markets. The work done in the last decades to improve the conversion efficiency of Solar cells shows crystalline silicon

based cell reaching close to the theoretical thermodynamic limit of 31%. Many of the emerging third generation technology based Solar cells can reduce manufacturing costs as a result of using a low temperature manufacturing process. These devices including Grätzel cell, organic photovoltaic cells, and nanotechnology based Solar cell also promise exceeding efficiency beyond the Shockley-Queisser limit in certain cases. These devices however are in the development stage with efficiencies in the range of around 10%.

Nanotechnology in the form of quantum dots, nanorods, carbon nanotubes and graphene has been shown to enhance the absorption of sunlight, make low cost flexible solar panels and increase the efficiency of photovoltaic cells beyond Shockley and Queisser limit. The ability of a quantum dot to change bandgap with the change in its size is used in increasing the amount of incident light absorbed by the photovoltaic cells, therefore improving efficiency. The efficiency of the Solar cell beyond the Shockley-Queisser limit is achieved by utilizing carrier multiplication through multiple exciton generation and capturing hot electrons which are lost as heat in solar-to-electric power conversion. Nanorods are also used to control the bandgap by varying the radius of the rods and using the quantum confinement effect which will lead to thinner devices for optimal absorption of incident light. However, because of low carrier mobility and inefficient charge transfer in semiconductor nanorods and CdSe quantum dots the use of carbon nanotubes in these devices is a better approach. Single wall carbon nanotubes are very efficient for transporting electrons and providing high electric field that provides an opportunity for exciton dissociation. They also provide higher carrier mobility and offer a wide range of bandgaps to match the solar spectrum, enhanced optical absorption and reduced carrier scattering for hot carrier transport. However, single wall carbon nanotube suffers from problems of implementation on a large scale. The epitaxial graphene, on the other hand, avoids these problems while retaining

many of the important electronic properties of carbon nanotubes. Graphene is capable of absorbing a wide range of light frequencies compared to semiconductors, which typically need to be layered together for this purpose. Nanotechnology based Solar cells are easy to make, more efficient, physically flexible and likely to be inexpensive even though they are still in infancy stages.

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KEY TERMS AND DEFINITIONS

Efficiency of Photovoltaic Cell: It is defined as the ratio of electrical power produced by a photovoltaic cell at any instant to the power of the solar input which sunlight is striking the cell measured in Watts /m². A major factor limiting the conversion efficiency is due to large bandgaps for low energy to be absorbed, while much of the

energy from electrons freed up by high-energy is lost as the electron is extracted.

Graphene Based Solar Cell: The epitaxial graphene is basically a single layer of graphite, consisting of a hexagonal array of carbon atoms, just like those found in bulk graphite. Recent work shows that graphene is highly conductive and highly transparent form of carbon which is a critical requirement for organic photovoltaic cell. It also shows outstanding thermal and chemical stability.

Multiple Exciton Generation (MEG): Multiple exciton generation involves the generation of more than one exciton from the absorption of a single photon. This a method is used to increase the efficiency of Solar cells beyond the Shockley-Queisser limit which has recently been demonstrated in quantum dots.

Nanorods: Nanorods are one dimensional structure which provides a directed path for electrical transport and are used to control the bandgap by varying the radius of rods and using the quantum size effect. The efficiency of quantum dot conjugated polymer Solar cell can be enhanced by using quantum confinement effect which will affect the length and width of nanorods leading to thinner devices for optimal absorption of incident light.

Photovoltaic (Solar) Cell: A photovoltaic cell is a Solar cell essentially made of a large area p-n junction diode. Energy from the incident photons creates excitation of the electron to the conduction band leaving behind a hole in the valence band resulting into electron-hole pairs or excitons in the case of organic semiconductors.

Quantum Dot: Quantum dots (QDs) are semiconductor nanocrystals of nanometers dimensions whose electrons-holes (excitons) are confined in all three spatial dimensions. Quantum dots are used

to improve efficiency of photovoltaic cells beyond standard thermodynamic limit. They have unique quantum optical properties that are not found in the bulk material due to the property of quantum confinement exhibited by the nanoscale structures.

Semiconductor Based Solar Cell: The conventional Solar cells are made of semiconductor material, usually crystalline silicon (c-Si) as light absorbing semiconductor. The first type of crystalline Solar cells is monocrystalline which are wafers, of about 0.3 mm thick, sawn from Si ingot of single crystal silicon. The second type of crystalline Solar cells are Polycrystalline (multi-crystalline) made by sawing a cast square ingot block of silicon first into bars and then wafers.

Shockley and Queisser Limit: Refers to the maximum theoretical efficiency of a Solar cell of around 33.7% assuming a p-n junction band gap of 1.1 eV (for silicon). In other words only 33.7% of all the power contained in sunlight falling on a silicon Solar cell, could ever be turned into electricity. In this model excitation energy above the bandgap is lost to heating and excitation energy below the band gap is not absorbed.

Single Wall Nanotubes (SWNTs): have a nanometer-scale diameter and exhibit ballistic electrical conductivity and are very efficient for transporting electrons. In addition SWCNT offers unique properties of offering a wide range of bandgaps to match the solar spectrum, enhanced optical absorption and reduced carrier scattering for hot carrier transport.

Solar Radiation: The annual energy input of solar irradiation on Earth exceeds the world's yearly energy consumption by several thousand times. Most of the energy coming from sun is in the visible and infrared part of the electromagnetic spectrum, with less than 1% emitted in the radio, UV and X-ray spectral bands.

Chapter 7

CuInGaSe Based Thin Films for Photovoltaic Solar Cells

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ABSTRACT

The authors present a brief overview of thin film photovoltaics, focusing on technologies that could play an important role in the manufacturing of next generation of solar cells. Over the past decade, there have been tremendous research and development efforts worldwide, to address the issues and challenges that thin film photovoltaic technologies are facing. Recently however, there has been great hope that advances in nanotechnology may open the door for breakthroughs in photovoltaics research. In particular, significant opportunities exist in the area of nanostructured materials, fueled by recent advances in equipment and processes that allow manipulation of materials at the atomic and molecular level, thus facilitating precise fabrication techniques and device characterization at the nanometer scale.

This chapter mainly focuses on two promising technologies, Copper Indium Gallium Selenide (CIGS) and nanocrystalline silicon solar cells. Heterojunctions based on CIGS have been studied for several years, and have shown very stable performance in field tests.

INTRODUCTION

We'll discuss various preparation methods for CIGS solar cells, the effects of composition ratio on the performance, doping profiles, alternative buffer layers, low cost fabrication techniques as well as global market trends. We will also investigate incorporation of nanoparticles such as quantum dots and quantum wires, and material

growth on flexible substrates. Nanocrystalline silicon films have also recently attracted attention for use in photovoltaic solar cells as they provide an approach which results in lower cost and higher efficiency than conventional solar cells. Furthermore, silicon based nanoparticles or superlattices may be integrated with other materials for bandgap-engineered devices. Designed appropriately, variation of the effective bandgap

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across the device allows a larger portion of the solar spectrum to be coupled into the solar cell increasing the conversion efficiency.

Non-vacuum methods for absorber deposition promise significantly lower capital expenses and reduced materials costs, and have been used to produce devices with efficiencies of up to 14%. Such efficiencies are already high enough for commercial up-scaling to be considered and several companies are now trying to develop products based on non-vacuum deposited CIGS absorbers.

The goal of the US Department of Energy (DOE) through its SunShot Initiative is to reduce the cost of solar energy systems to reach grid parity. The \$300 million over the next five years, Photovoltaic Manufacturing Consortium (PVMC) initiative awarded to the College of Nanoscale Science and Engineering (CNSE) and to International SEMATECH from DOE will be presented. The PVMC is primarily focused on CIGS thin film technology. The goals of the PVMC is to promote supply chain collaboration in the US, advance large-scale solar manufacturing, boost American competitiveness, reduce cost, and drive the deployment of solar energy. Currently the cost of CIGS thin film based panels is at \$1.10/Watt.

As the demand for sustainable and environmentally friendly energy sources continues to increase, there exists an urgent need to develop materials, products, and processes that will make these sustainable energy conversion technologies more efficient and economically attractive. Solar energy conversion, and in particular photovoltaics, is in the forefront of the sustainable technologies holding promise to provide a clean, inexhaustible source for the production of electric power. Although the increasing demand for clean energy has motivated a record expansion of photovoltaic facilities worldwide in recent years, to date this technology represents only a fraction of a percent of the total electricity production. Tremendous opportunities exist for the technology to become much more pervasive, provided that there will be advances in areas such as cost reduction in

the materials and installation, development of solar cells with increased quantum efficiency, and expanded application space, such as for example, flexible modules, building integrated photovoltaics, light-weight modules for portable applications, etc.

According to European PV Industry Association, while the European Union has dominated the world market for years, the rest of the world has clearly the biggest potential for growth. In 2010, the EU was the world's largest PV market. With more than 13 GW installed in 2010, its total installed PV capacity surged from 16 to almost 30 GW. PV makes economic as well as environmental sense and is a sustainable solution to the energy needs of countries around the Equator. Driven by local and global energy demand, the fastest PV growth is expected to continue in China and India, followed by South-East Asia, and Latin America. The PV potential of the Sunbelt countries could range from 60 to 250 GW by 2020, and from 260 to 1,100 GW in 2030, representing 27% to 58% of the forecast global installed PV capacity by then (European PV Industry Association, 2011). The rest of the world accounts for a 3 GW market for PV. Japan and the USA approached the GW mark in 2010 and are expected to continue growing in 2011.

The vast majority of commercially available photovoltaic solar cells and modules are made of silicon, in its various forms (Ullal, 2007). Typically, either single-crystalline, or polycrystalline, or amorphous silicon are used in the fabrication of solar panels both for residential and large scale commercial photovoltaic systems. Each of these technologies offers a well-established price to performance ratio and specific cost and benefit advantages depending on the particular application, location, available area, aesthetics, etc. However they are all "first generation" technologies suffering from performance limitations due to the properties of the bulk silicon material used. Some improvements in the performance have been achieved with optimization in the solar

cell design such as the SANYO Heterojunction with Intrinsic Thin Layer technology etc., electrical contacts, and purity of the material (Tanaka, 2003). However, to significantly improve the efficiency and/or reduce cost, the issues with the fundamental limitations in the optical properties of silicon have to be addressed. Single crystalline silicon solar cells currently provide relatively good power conversion efficiency, however they suffer from high cost. Crystalline silicon has low absorption coefficient, thus quite thick material, 200 to 300 microns, is needed for efficient light absorption, increasing the material cost. Its band gap is also narrower than that desired for solar cell applications. Solar light with energy much larger than the silicon bandgap, when absorbed by the material is converted into heat rather than electricity thus reducing the efficiency.

Polycrystalline silicon or amorphous silicon solar cells are available at lower cost; however their conversion efficiency is lower compared to single crystalline based cells. In addition, amorphous silicon shows photodegradation and reduced stability under light illumination, which is known as Staebler-Wronski effect. Because of this effect, the cell efficiency drops when the cell is exposed to light. The degradation acts primarily on the fill factor (FF) and the short circuit current (I_{sc}), whereas open-circuit voltage remains almost constant. Degradation can be reversed, but only by exposing the cells to a temperature of approximately 160°C. This effect has not been fully explained. One possible explanation is that the recombination of light-generated charge carriers causes weak silicon-hydrogen bonds to be broken in the amorphous material, thus creating additional defects that lower the efficiency and increase serial resistance.

In spite of these drawbacks, silicon is still the dominant material in commercial photovoltaics. One of the main reasons is that silicon is by far the major player in today's semiconductors market and the most important material, dominating the microelectronics industry with about 90% of

all devices sold worldwide being silicon based. Therefore, the already very well established infrastructure and silicon processing technology (silicon is the material that has been most extensively studied for many years) was easily transferred to the photovoltaics industry. Silicon's dominance in microelectronics and photovoltaics is mostly due to the following aspects, which provide benefits that other electronic materials cannot easily match: (i) Silicon is non-toxic, relatively inexpensive (silicon comprises about 26% of the earth's crust which makes it second in abundance only to oxygen), easy to process (a very well established industrial infrastructure in silicon processing exists around the world), and has quite good mechanical properties (strength, hardness, thermal conductivity, etc.) and (ii) Silicon possesses two of the most outstanding natural dielectrics, silicon dioxide (SiO_2) and silicon nitride (Si_3N_4), which are essential for device formation. In particular, SiO_2 , which is the basis of the metal-oxide-semiconductor devices (MOS) can be grown thermally on a silicon wafer, it is chemically very stable and can achieve a very high breakdown voltage. The interface defects of the thermally grown SiO_2 by reaction of oxygen with a silicon wafer are several orders of magnitude lower than those of any deposited film.

Especially for photovoltaics, the absorber is a single element layer which makes it easier to process compare to other absorber materials which consist of a combination of elements. Back draws of silicon based solar cells is the high cost of silicon. Even though the current price is lower than \$50/kg it is still expensive while a couple of years ago the silicon price exceeded \$300/Kgr. However, many believe that the future in photovoltaics will involve a major market penetration from novel technologies based on thin films and nanoscale materials.

Various types of thin film materials and devices such as CIGS (Copper Indium Gallium Selenide – CuInGaSe_2), CdTe, polymer based materials, etc., but also nanoscale silicon based

devices (in addition to the old technologies of amorphous and polycrystalline silicon), are being investigated for the next generation photovoltaic solar cells. In particular some of these thin film technologies have received major funding (especially since there has been a shortage of refined, device quality, silicon material during the recent years) and there have been major achievements and significant progress in improving efficiency and reducing cost.

The National Renewable Energy Laboratory (NREL) has claimed a world record for CIGS thin-film solar cell conversion efficiency of 19.9% (Repins, 2008). The conversion efficiency for CIGS is now close to that of multi-crystalline silicon-based solar cells, according to NREL. Thus, the efficiency of thin film solar cells is now achieving its goal of matching polycrystalline silicon in performance. One of the CIGS deposition methods lately investigated for scale up and industrial production is thermal evaporation. As compared to other deposition methods, thermal evaporation produces the highest efficiency thin film solar cells and has the lowest materials costs with high material utilization driving down the manufacturing cost per watt.

During the last years Veeco Inc. started an effort to introduce in the market multi-source evaporation systems which could process large area 1.1m x 1.4m glass panels. The modular architecture of the system would allow PV manufacturers to scale output according to their needs. Recently, Veeco decided to pull from CIGS tool development efforts but decided to continue its unique thermal deposition source technology that could be attractive to equipment companies.

GIGS BASED PV: BENEFITS AND CHALLENGES

CIGS is one of the most promising thin film materials that is closer in being at the level of development and manufacturing. It is possibly

the only material to directly compete with single crystalline and polycrystalline silicon in the markets. CIGS offers several advantages over silicon, with the most important being the promise of achieving lower cost approaching less than \$1/Watt, which is considered an important target in the PV industry. Crystalline silicon, even though is a single element material, is still quite higher in cost than this benchmark due to the high cost of raw material. The cost benefit of CIGS is mostly due to a lower manufacturing cost of the material and high production yield. In addition on the technical arena, CIGS as a direct and tunable bandgap material, offers high absorption coefficient therefore very thin material of only a couple of microns thick ($\sim 1\text{--}2\ \mu\text{m}$) is enough to absorb most of the light incident on the solar device. Therefore, significant cost savings could be reached, since very little material is used. A second very important advantage of CIGS is that it can be deposited on flexible substrates by roll to roll process, resulting in modules that will have an extended application space, such as in building integrated photovoltaics (BIPV), consumer electronics, applications that require light-weight modules (aerospace applications, for example) and portable devices. Flexible, light-weight photovoltaic modules with high conversion efficiency will provide a major breakthrough, allowing photovoltaics excellent applicability in many areas. CIGS provides the best conversion efficiency among the thin film technologies. In a laboratory environment, a single junction CIGS based thin film solar cell has shown to achieve a 19.9% efficiency (Contreras, 2005). Typical efficiency of CIGS modules is about 10 – 13%. Besides higher efficiency, CIGS offers other advantages as well over other thin film technologies. For example, tests have shown that CIGS does not degrade in sunlight, which is a major concern with other thin film technologies such as amorphous silicon, and results in reduced efficiency over the years. In addition, this technology is environmentally safe, since cadmium is in very small quantities and also

bonded to sulfur while it is manufacturing ready with strong research base to build on and has the immediate potential for job creation within the United States. For all the above reasons, CIGS technology has attracted major interest, and in recent years there are many companies worldwide that have heavily invested in this material.

Thin-film CIGS based devices also rely on a larger combination of elements making it more challenging to achieve the right stoichiometry, crystallinity, and uniformity, especially in large deposition areas for monolithic integration. In addition some of these elements are costly and rare (e.g., Ga, In, Se). These issues could limit their use in large scale deposition for production. Several technical challenges CIGS technology is facing are the absorber and device complexity, the lack of fundamental understanding of materials and processing in the absorber layer, buffer layer, and front/back contacts level. Other areas include materials composition and their integration into a device, engineering of interfaces and tight control of impurities. There is also a lack of widely accepted deposition process and processing parameters as well as reliability testing and scientific understanding of possible degradation mechanisms. CIGS modules have shown long-term stability. However, performance degradation has also been observed. CIGS devices are sensitive to water vapor; e.g., change in properties of ZnO. Thin film barrier to water vapor and new encapsulants and less aggressive application process are challenges that need to be addressed. A lot of effort is needed in high performance, high volume manufacturing equipment and real time, in-line metrology. Controls and diagnostics based on material properties and film growth lead to higher throughput and yield, improve reliability and reproducibility of the process, and result higher conversion efficiency. In addition, there are no roadmaps, standards, protocols, certifications while scaling in manufacturing - small-area champion cell to large area still remains the most important issue.

Currently, there are significant research and development efforts to consider alternative materials that use lower cost and more abundant elements, while maintaining the advantages of CIGS absorbers, such as direct and tunable band gap, high efficiency and low cost. These efforts are focused on vacuum and non-vacuum techniques of kesterite-based $\text{Cu}_2\text{ZnSn}(\text{S/Se})_4$ (CZTSS) thin-film solar cells, in which the indium and gallium from CIGS are replaced by the readily available elements zinc and tin.

The advancement of new generation of thin solar cell technology toward more efficient and lower cost PVs resembles the advancement of micro/nano chip fabrication over the last two decades. The development of integrated circuits (ICs) is known as Moore's law. According to this law, the number of transistors per unit area is doubling every 18 months. There is a debate among PV community, if Moore's law can be applied solar cell development efforts. A possible answer is that while not directly transferable, the technical features of Moore's Law have analogs in PVs (Bowden, 2010). The technical parameter that drives Moore's Law is the gate length on the transistor level. A shorter gate length both improves computer clock speed and reduces costs by allowing more transistors on a silicon wafer, i.e. higher transistor density (transistors/cm²). As expressed for ICs, Moore's law does not directly translate to PV, as neither efficiency nor module area scale by large factors. For example, the analog to transistors/cm² is power generated per unit volume of material in the solar cell, i.e. W/cm³. In PVs, the volume is the relevant parameter rather than surface area (as in transistors) both because PV price is dominated by material volume in large-scale production and because performance relates to material volume. For example in real cell devices, several critical characteristics such as absorption and recombination relate to material volume.

Decreasing solar cell thickness and increasing concentration are two possible ways to decrease

material volume while increasing efficiency. A thinner solar cell enables higher W/cm^3 by increasing the efficiency and by decreasing material use, making solar cell thickness an analog to gate length in transistors. During the last ten to fifteen years, the thickness of silicon solar cells has decreased from 1,000 μm to 200 μm or less today. While in new thin film technologies the silicon thickness is in the range of 20 μm to 2 μm . On this respect, CIGS based solar cells are thin film devices with targeted thickness of CIGS absorber layer approximately 2 μm . The change in thickness is numerically similar to the change in gate length in ICs, which decreased the last twenty five years from about 5 μm to under 30nm today. The combination of increased efficiency, thinner wafers, concentration and other effects will enable a five-order of magnitude improvement in W/cm^3 , similar to that experienced in transistors/ cm^2 in Moore's Law.

Cu(InGa)Se₂ Deposition Methods and Device Fabrication

CIGS based solar cells are multilayer devices consisted of a substrate, a metal back contact, a Cu(InGa)Se₂ layer which serves as light absorber and forms the p-type material of the p-n junction, a wide-bandgap n-type material – typically CdS – to complete the junction, and a transparent conducting oxide forming the front side contact. The structure is completed with a top metallic grid contact of Ni/Al.

The most common substrate used is soda lime glass, however, in recent years light-weight and flexible substrates such as polymers or metal foils are been explored. The use of soda lime glass substrate offers several benefits. Besides providing a material, which has a very good thermal expansion match to the CIGS layer, it also provides a source for sodium (Na) which diffuses from the substrate to the CIGS absorber layer. It has been shown that Na incorporates in the grain boundaries and the surface of the CIGS layer, and it is

necessary for increasing the efficiency of the solar cell. For substrates that do not provide a natural sodium source for diffusion, Na needs to be incorporated by other means during the fabrication process leading to an additional step. One of the disadvantages of the glass substrate is that it is not flexible. Flexible and light-weight solar cells will enable many applications, as they can be integrated easily on any contour surface. Photovoltaics on vehicles and building-integrated photovoltaics (BIPV) are only a few of the applications that will benefit from flexible solar modules. Polymers can provide a flexible and light-weight substrate, but they impose limitations in the processing substrate temperature that can be used. Typically, heat-resistant polymers such as polyimides are used, which can withstand temperature up to 500°C, which is within the acceptable range for good quality device fabrication. Metal foils offer an additional choice for flexible substrates. Stainless steel, titanium, or molybdenum are typically used (Dhere, 2005). These metal foils can withstand higher processing temperatures and can be used in roll to roll process such as 1m width. One of the major issues metal substrates introduce is that impurities from the foil can diffuse to the absorber layer reducing the efficiency of the solar cell. To eliminate this possibility, a barrier layer is required between the metal foil and the CIGS absorber to reduce or possibly eliminate the diffusion of impurities. Usually nitride such as TiN or TaN or oxide layers such as Cr₂O₃ or SiO₂ could be used as impurities diffusion barriers. Another issue is that the surface of the metal foils fabricated in a machine shop is contaminated by hydrocarbons and is also very rough. Thus, additional cleaning and surface treatment steps are required prior to barrier layer deposition.

One of the biggest advantages of the CIGS solar cells over their silicon counterparts is the very efficient light absorption offered by the Cu(InGa)Se₂ absorber layer. For a good light absorber material, a direct bandgap semiconductor with high absorption coefficient is required.

As CIGS provides an excellent absorber, only a very thin layer of about 2 – 3 μm in thickness is required to absorb the incident photons. On the contrary, crystalline silicon having an indirect and relative small bandgap of 1.1 eV is not an efficient absorber. About 300 μm to 200 μm of silicon is required for effective light absorption, i.e. approximately 100-times thicker material than that required with CIGS. Another advantage of the CIGS absorber is that its bandgap can be tailored over a range between 1.0–1.7 eV, by varying the Ga and In content in the alloy, allowing a design that can match better the solar spectrum.

Several vacuum and non-vacuum process methods are used for the deposition of the CIGS absorber layer. Vacuum deposition techniques include magnetron sputtering by a single CuInGa target with premixed elemental composition or by a combination of Cu, In, CuGa targets followed by selenization (two step process) and thermal evaporation from single element sources (one step process). Non-vacuum methods include ink printing, electroplating, spray pyrolysis, ultrasonic spray coating, and processes involve deposition from a chemical bath solution. Each deposition method has several advantages and disadvantages. Even though, thermal evaporation is the method of choice for small area samples, to date there is no single technique widely accepted to deposit CIGS films which could result in large area deposition. Several intense research and development efforts are under way, to prove that one deposition technique can be the dominant for large areas. A key problem for the commercialization of CIGS technology is scaling up laboratory techniques to the industrial level while maintaining a high conversion efficiency of cells and modules. Key issues to solve are thickness and composition uniformity across large areas such as 2 ft x 6 ft on glass, or on 1 m wide metal foil. A possible approach is the use of already available in the market production equipment such as magnetron sputtering systems. Sputter deposition is controllable and reproducible method in large area substrates. However, the

absorber deposition process is complex and the industry continues to search for economical and reliable methods to grow device-quality CIGS in large areas and integrating such devices to form modules. NREL has developed one step thermal evaporation process to deposit CIGS films high from point sources of Cu, In, Ga and Se. However, uniform and fast delivery over large areas of these elements with a satisfactory compound formation process capable of producing high quality CIGS, currently presents a significant challenge.

In the two step process of sputtering followed by selenization, the metal precursors (Cu, In and Ga) are deposited on a substrate via rf or dc-sputtering (printing or electroplating as non-vacuum techniques could also be used) followed by exposure to a selenium atmosphere and heat. The selenium atmosphere may originate from a gas of hydrogen selenide (H_2Se), or diethyl selenide ($(\text{C}_2\text{H}_5)_2\text{Se}$), or in the form of a vapor from a solid selenium source. The issue with H_2Se is that it is very toxic while $(\text{C}_2\text{H}_5)_2\text{Se}$ is less toxic but five-times more expensive than H_2Se . In sputtering, Cu, In and Ga source atoms are ejected from a solid target material such as In, Cu, and CuGa (75%,25%) or CuInGa due to bombardment of the target by energetic ions. As mentioned, sputtering is a mature thin film deposition process used extensively in other industries, including flat panel displays, semiconductors, etc. It is also adopted for CIGS large area deposition, in part, because the scalable nature of the sputtering process.

The metallic precursors are deposited sequentially on a double layer of molybdenum on glass substrates by magnetron sputtering. Precise control of film composition, density, and substrate temperature are critical factors in making device quality CIGS films. For example, the atomic composition of the resulting films sputter deposited from Cu, In, and Cu/Ga sputtering targets is $\text{Cu}/(\text{In}+\text{Ga})=0.895$ and $\text{Ga}/(\text{In}+\text{Ga})=0.298$. These metallic precursors are then selenized in Se atmosphere followed by sequential deposition of CdS, i-ZnO, and ZnO:Al layers and metal contacts to

fabricate CIGS devices. Devices fabricated with two step process exhibit conversion efficiency in the range 10% to 15% under AM1.5. Several research groups have investigated physical and electric properties of the CIGS thin films by different temperature profiles under controlled Se vapor pressure. Scaling up of this process requires the adoption of the simplest possible cell structure in order to minimize cost.

An interesting deposition method is a two step CIGS process in which the precursor films were deposited at substrate lower than room temperature. CuInGa precursor thin films were deposited using simultaneously CuGa (75-25 at%) and In₃” diameter target material by magnetron sputtering. The precursor films were deposited on Si, Mo/Si and glass substrates at -80°C and room temperature. The films characterized by various characterization techniques such as Rutherford Backscattering Spectroscopy (RBS), Inductive coupled plasma mass spectroscopy (ICP-MS), Auger Electron Spectroscopy (AES), Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM) and X-ray diffraction (XRD). Precursors films deposited at -80°C found to possess smooth surface morphology with a 90% reduction in all roughness values (average roughness, root-mean-square) and are more dense and homogeneous in structure compared to precursors deposited at room temperature.

The characterization results revealed information on the micro-chemical and micro-structural properties of the CuInGa precursor films. The findings supported that depositions at -80 °C result in dense, homogeneous and smooth precursor films due to the retardation of diffusion of In out of the Cu-Ga system (Hanssen, 2001). There is a strong correlation between substrate temperature and crystallographic structure, density, homogeneity and surface morphology. The precursor material was quenched on cold substrates, locking the particles in place and resulting into homogeneous, smooth and dense thin films. The precursor films thickness was 600 nm films. Other groups have

reported CuInGa precursor thin films with mean roughness values below 200 nm for the same precursor film thickness. In this work we were able to produce dense, smooth and homogeneous CuInGa precursor thin films with RMS roughness values below 20 nm (Gremenok, 2004).

It was found that the selenization kinetics and chalcopyrite syntheses strongly depend on the state of the metallic precursor film after deposition. The film morphology and homogeneity has a great influence on the reaction process. Precursors with rich In phases on the surface will give rise to badly reproducible interfaces with selenium and can give rise to significant change in absorber synthesis kinetics and will therefore yield a bad reproducibility of the process. The morphology of the precursor thin films stays unchanged even though the crystallographic phases become similar at a post anneal at 200 °C (Berwian, 2005). Increasing the process temperature during precursor thin film formation does not change the morphology of co-sputtered and sequentially sputtered films. Because of the strong influence of the precursor sputter process on the surface morphology, homogeneity and the related absorber formation, it is of great importance to have smooth and homogeneous precursor thin films. The metallic precursors were selenized by annealing in elemental selenium environment and devices fabricated exhibited power conversion efficiency in the order of 5-6% under AM1.5 global solar photon flux normalized to 1000W/m².

Another example of CIGS deposition is the work reported by A. Delahoy *et al.* (Delahoy, 2004). The investigators deposited CIGS on 0.43m² modules which consisted of 71 monolithically integrated cells with each cell consisted of Mo/CIGS/CdS/i-ZnO/n-ZnO. The CIGS was grown by first depositing an (In_xGa_{1-x})₂Se₃ layer by delivering In, Ga, and Se to a heated substrate, and then deposited a Cu layer by sputtering (Delahoy, 2004). The stacked Cu/(In_xGa_{1-x})₂Se₃ layer was treated in a Se atmosphere followed by delivery of In, Ga, and Se to complete the CIGS deposition. High-quality CIGS has been produced

with Cu sputtered. Using a standard R&D-scale multi-source evaporator and stationary substrates, a cell efficiency of 13.5% was achieved with the Cu sputtered under AM1.5. The measured external quantum efficiency versus wavelength for a hybrid process cell without AR coating was also measured. The devices showed very good carrier collection and a high peak QE stemming from the reduced reflection resulting from the roughness of the CIGS. The band gap of the CIGS was ~ 1.11 eV, was determined by extrapolation of the tangent at the inflection point of the QE curve.

To address the need for a simpler, scalable, low-cost deposition technology for CIGS, research groups are trying to employ one-stage magnetron sputtering from a single $\text{Cu}(\text{In}_{0.7}\text{Ga}_{0.3})\text{Se}_{0.6}\text{Na}_x$ target (initially, with alternative compositions developed as needed) to deposit CIGS on up to 4" square Mo-coated glass substrates followed by selenization to crystallize the films. To investigate composition effects, a Cu target could be used in the same sputtering system to supply additional Cu. The motivation for this work was the need to improve the ease and uniformity of CIGS delivery (as compared to delivery by linear source evaporation) in the case of large-area substrates. This work is currently in the development of a baseline process which could be followed by optimizing a manufacturing-worthy process.

The high efficiencies achieved with CIGS thin films, with a world-record efficiency CIGS solar cell of 19.9% was deposited by co-evaporation through a three-step process. Co-evaporation has difficulties in scaling-up for a large-manufacturing system because of its complexity. Along other deposition techniques, the two-step process, in which the selenization step follows the sputtering step of the metallic precursors, seems to be the most feasible for industrial production use.

Co-sputtering of CuInGa precursor thin films, from a dual target approach was proposed to form homogeneous precursor material. However, for deposition at room temperature and higher temperatures, Indium segregates, and forms In-rich

islands on the film surface, while the CuInGa precursor film becomes rough and inhomogeneous in structure. To reduce In segregation and improve homogeneity and surface morphology, a bi-layer CuGa/In approach is reported. This bi-layer structure increases homogeneity and reduces surface roughness, nevertheless, still gives rise to an In-rich islands on the surface, due to phase separation at room temperature or higher temperatures during deposition.

PVD evaporation of single elemental layers on a substrate cooled to -160°C resulted in smooth Cu and Ga thin films. The cooled substrate approach has not further investigated to date in the form of multi compound thin films obtained by co-sputtering. This is the reason CNSE has further investigated the improvement of precursor morphology and homogeneity using a liquid N_2 cooled substrate before co-deposition. The chemical composition, sticking coefficient, and the morphology and crystal structure of the precursor thin films are strongly depended on the temperature of the substrate. The deposition of CuInGa precursor thin films with a dense and smooth morphology and homogeneous in structure has been demonstrated using this approach. In addition, this deposition process can easily be accommodated to an industrial mass-production system.

In addition to sputtering technology, thermal evaporation in vacuum from point sources, as one step process, provides excellent control of CIGS film composition. Evaporation is the method traditionally used for the absorber layer and has produced to date the highest power conversion efficiency (19.9%) solar cells. It involves co-evaporation of elemental Cu, In, Ga, and Se in a high vacuum (10^{-7} torr) chamber. During deposition the substrate is heated at temperatures of $400^\circ\text{C} - 600^\circ\text{C}$. Higher temperatures lead to better material structure, however for polymer substrates the temperature is kept at the lower end of the range. Boron nitride Knudsen cells are typically used to hold the source material. The temperatures required for evaporation of the source materials

are as follows: $T(\text{Cu}) = 1350\text{ }^{\circ}\text{C}$, $T(\text{In}) = 1000\text{ }^{\circ}\text{C}$, $T(\text{Ga}) = 1100\text{ }^{\circ}\text{C}$, and $T(\text{Se}) = 300\text{ }^{\circ}\text{C}$. Precise temperature control of the sources typically leads to excellent control of the film parameters and the best performance films. Another benefit of this method is that it allows independent control of each element. Therefore by adjusting for an appropriate ratio of $\text{Ga}/(\text{In}+\text{Ga})$ gradient, bandgap engineered devices with a bandgap gradient can be produced. Furthermore, this process allows for the growth of Cu rich films. Although this method provides excellent results for laboratory or small area applications, it is not very well suited for large area, high throughput production.

A variation used in several commercial processes involves using an in-line array of evaporation sources that deposit material on substrates that are on a moving heated stage. Another approach involves a two-step process. In the first step copper, indium and gallium are co-evaporated. The resulting film is then annealed in a selenide atmosphere to form the CIGS structure. Several companies have developed vacuum equipment designed for heating and coating large-area moving substrates in which the materials (e.g. Cu, In, Ga, Se) are supplied using their own proprietary linear thermal source technology (Delahoy, 2000; Delahoy, 1996). The use of elemental selenium rather than toxic H_2Se or expensive $(\text{C}_2\text{H}_5)_2\text{Se}$ gas can help make for a safe manufacturing environment. These choices concerning film deposition, substrates, and source materials help to minimize the processing costs of CIGS.

Besides thermal evaporation, sputtering can also be used as an alternative vacuum deposition technique. This is a two-step process. First Cu, Ga, and In are co-sputtered in vacuum using con-focal sputtering guns for better uniformity. The second step involves selenization of the as deposited film by reaction with Se in an inert gas environment. As an alternative, a Se layer may be evaporated on the film followed by rapid thermal processing (RTP).

Another possible alternative to CIGS absorber layer which has been investigated is CuInAlSe (CIAS) (Dwyer 2010). It was found that in CIGS devices as more Ga is introduced in the absorber layer the energy band gap (E_g) of the absorber layer increases. For example, the E_g of CIGS films with $(\text{Ga}/(\text{Ga}+\text{In})) \sim 0.5$ is approximately 1.3 eV. However, as more Ga is introduced beyond this point, the device efficiency is decreased. There are several explanations about this behavior. A possible one is that high-Ga atomic concentration in CIGS films introduces mid-gap Ga defects which act as recombination centers. Replacing Ga with Al can further increase the E_g and introduce fewer structural defects due to the smaller size of Al atom compared to Ga. Record CIAS lab scale device efficiency has reached 16.9% using a co-evaporation process (Marsillac 2002). In Dwyer *et al.* work, CuInAl precursor films with varying Al/(In+Al) ratios were co-sputtered onto Mo coated soda-lime glass substrates. Metal precursor films were then selenized under vacuum conditions using thermally evaporated elemental selenium. Devices fabricated using CIAS as absorber layer with ~ 2.0 atomic % aluminum, exhibited under AM1.5 power conversion efficiency 5.2%.

Although vacuum deposition techniques result in good quality films, they are rather expensive and do not always lead to cost effective high-throughput manufacturing. Most materials via evaporation and sputtering are lost and recycling is a difficult process if utilizing vacuum processes. The advantage of non-vacuum or solution processes is that the deposition rates can be much higher. With vacuum deposition, you are depositing at a rate of less than ten microns an hour. With solution processing, with one sweep, one can have a big fraction of the targeted thickness of the deposited film. Several alternative non-vacuum methods have been developed for fabrication of CIGS. Among the most promising non-vacuum techniques is the use of metal precursors followed by a selenization process. The first step involves

the deposition of Cu, In, and Ga on the substrate by screen printing or spraying. A precursor ink consisting of nanoparticles of Cu, In, and Ga oxides is used for this process. The desired ratio can be adjusted very accurately within the ink. An ink-jet printing method can be used to deliver the ink very accurately resulting in a fast method that minimizes wasted ink. Selenization of the resulting films is then performed either by using an RTP process, or by exposing the films in an atmosphere of H_2Se and N_2 gases.

Sono-Tek Corporation, Milton, NY, USA has developed an ultrasonic coating technology for spraying CIGS solutions and CdTe layer chemistries in thin film solar cell manufacturing. This technology was demonstrated at the 26th European Photovoltaic Solar Energy Conference (EU PVSEC) in Hamburg, Germany (www.sono-tek.com). The coating equipment costs a fraction of the cost of chemical vapor deposition (CVD) and sputtering deposition methods while the ultrasonic nozzles are advantageous for depositing uniform thin films of nanosuspensions. Using high frequency sound vibrations, the nozzles atomize liquid solutions to form a soft spray of micron-sized droplets. The nozzles are non-clogging precision atomizing devices, whose high frequency vibrations break up any agglomerations in solution throughout the entire coating process. This is particularly valuable when depositing cadmium-based suspensions where agglomerations can result in non-uniform distribution of particles and lower cell efficiency. Ultrasonic atomization creates a very stable process with highly repeatable thin films, and uniformities as low as $\pm 2\%$. An aerosol assisted CVD process using both solid and liquid ternary single-source precursors was performed in a vertical atmospheric pressure cold-wall reactor with a commercial ultrasonic nozzle (Sono-Tek 120 kHz) (Jin, 2003). One important prerequisite for single-source precursors is a lower decomposition temperature than the substrate temperature so that film deposition can be initiated on polymer substrate without thermal degrada-

tion. It was successfully shown that AACVD is a useful alternative to conventional CVD when the vapor pressure of the precursor is too low for CVD, since it easily delivers precursors to a heated substrate by spraying it into a hot zone, followed by evaporation over a heated substrate.

As it is already mentioned, CZTS is another absorbing thin film to replace CIGS. It utilizes only abundant and cheaper metals and is expected to lower production costs. Performance and production yields for CZTS, in large scale production, can be as competitive as CuInSe (CIS). The zinc and tin supply are more abundant compared to indium and gallium making the supply situation more stable. One other possibility is to replace the selenium in the record efficiency cells with sulfur. CZTS has a similar crystal structure to that of chalcopyrites. The optoelectronic properties of CZTS do not seem to vary very much from that of CIGS as well, showing similar light absorption properties. However, CZTS does offer a potential benefit in that it has a higher band gap (that is similar to that of CdTe), meaning higher output voltages compared to CIGS or c-Si solar cells.

Devices based on CZTS, deposited using vacuum equipment such as sputtering from pressed targets of quaternary materials or by sequential deposition of metal layers such as Cu/Sn/Zn, have achieved efficiency as high as 6.8%, while liquid-based deposition approaches of the absorber layer led to devices with power conversion efficiency of 10-11% (Katagiri, 2009). This achievement attracted more attention to non-vacuum development of kesterite materials and brought this technology into a range of possible commercial interest. There are several technical barriers which have to be overcome in order to even further increase the efficiency of these devices to the 14-15% range. Among the issues that limit the cell performance and need to be addressed are loss mechanisms such as interface recombination, high series resistance and low minority carrier lifetime. In addition understanding of long-term device stability and solving issues such as composition,

texture, and thickness uniformity in large areas are important to move this technology forward (Mitzi, 2011).

Copper-indium-gallium-sulfur-(di)selenide thin-film photovoltaic panels are currently produced by several companies such as Stion which is based in California. Stion may also be the only CIGS player that has been pursuing a tandem-junction architecture in which their first-generation product (with ~11% efficiency at the panel level) is actually the bottom device of what will ultimately be a mechanically stacked dual structure (www.stion.com).

As mentioned already, the as prepared CIGS absorber layer is a p-type material. Doping occurs naturally in the material by intrinsic point defects and vacancies in the crystalline lattice. The next layer in the structure is an n-type material that must have a larger bandgap to allow photons to pass through it, so that they can be absorbed in the CIGS absorber layer. This is called the “window layer” or the “emitter layer”. Cadmium sulfide (CdS) is commonly used, which is a direct bandgap material with a bandgap of 2.4 eV. Some of the light in the blue region of the solar spectrum is therefore absorbed in the CdS layer, however most of the generated carriers are lost to recombination and do not contribute to the photocurrent. Typically a CdS film of thickness of 40–80 nm is deposited by chemical bath deposition. The as deposited CdS film is an n-type material because of native defects. Therefore it is used to form a p-n junction with the p-type CIGS absorber layer.

For a material to be a suitable buffer layer a few requirements must be met. First a high band gap is desired, with high light transmission below the band edge to allow maximum light generated current. CdS has a band gap of 2.4 eV, corresponding to a photon wavelength of 517 nm. Photons with energy above 2.4 eV can be optically absorbed, reducing the available light to generate electron–hole pairs in the absorber layer. A higher band gap film that allows light transmission down to 370 nm (3.35 eV) is desired. Second, films

must form a continuous coating over the absorber layer at low thicknesses. Pinholes in the film can cause localized degradation in electronic properties, increasing tunneling and lowering contact potential at the junction. This continuous coating must be formed at low thicknesses (<100 nm) to avoid losses in light transmission associated with thicker films. The conduction band offset (CBO) that is created at the CIGS/buffer interface is also important, especially for wide band gap absorber materials for both single and multijunction devices. The CBO of the highest efficiency CIGS cells (band gap 1.15 eV) at the CIGS/CdS interface is 0.3 eV. This is a nearly optimal value. As the absorber band gap is increased buffers with wider band gaps than CdS are needed to maintain this ideal CBO value (Contreras, 2002).

Several alternative materials to CdS are being explored to serve as emitter layer, mainly to avoid the environmental issues involving the use of cadmium which is considered as highly toxic even though it is bonded to sulfur and it is not in free form (Dwyer, 2010). Some of the alternatives may also offer added benefits, such as wider bandgap and a dry or vacuum fabrication process which will be more compatible with the rest of the device. Some of the alternative emitter materials include Zn_xS , $\text{Zn}(\text{O},\text{S},\text{OH})$, ZnSe , In_2S_3 , and $\text{Zn}_{1-x}\text{Mg}_x\text{O}$. These materials may be deposited by vacuum deposition techniques such as atomic layer deposition (ALD), sputtering, MOCVD, PVD, etc.

From a market perspective, PV manufacturing in the US is at risk. Equipment and materials suppliers expressed their concern to members of the US House and Senate over the possibility that some incentives -- the Manufacturing Tax Credit and the 1603(c) Grant in Lieu of Tax Credits -- will not be extended. This could lead at least some of them to consider manufacturing overseas, where tax holidays, land, and less expensive labor are easier to come by. But there is more to manufacturing than policy. At the second annual North American PV Fab Managers Forum, organized by SEMI in conjunction with Intersolar North

America 2011 put the PV solar manufacturing supply chain in the US under the microscope. This year's theme was "thin film," focusing on CIGS and CdTe. The Forum featured manufacturers, equipment and materials suppliers, and other contributors, before the backdrop of global and US thin-film market trends and developments -- and yes, some policy. Cost drivers, efficiency barriers, and supply-chain wide dialogue around shared challenges are issues of great importance and interest which were all discussed.

The tenth edition of the PV Status Report, published by the European Commission's Joint Research Centre (JRC), indicates that in 2010, the photovoltaic (PV) industry production more than doubled and reached a world-wide production volume of 23.5 Gigawatts (GW) of photovoltaic modules (Jäger-Waldau, 2011). Since 1990, photovoltaic module production has increased more than 500-fold from 46MW to 23.5 GW in 2010, which makes photovoltaics one of the fastest-growing industries at present.

In 2010, the world-wide photovoltaic production more than doubled, driven by major increases in Europe. For 2010 the annual market volume of newly-installed solar photovoltaic electricity systems varies between 17 and 19 GW, depending on estimates. This represents mostly the grid-connected photovoltaic market, as there are no reliable estimates available for the non grid-connected market. The report shows that with a cumulative installed capacity of over 29 GW, the European Union is leading in PV installations. By the end of 2010, European photovoltaic installations provided more than 70% of the total world-wide solar photovoltaic electricity generation capacity.

The photovoltaic industry has changed dramatically over the last few years. China has become the major manufacturing center for solar cells and modules followed by Taiwan, Germany and Japan. Among the twenty biggest photovoltaic manufacturers in 2010, only four had production facilities in Europe or North America, namely First

Solar (USA, Germany, Malaysia, Vietnam), Q-Cells (Germany and Malaysia), REC (Norway and Singapore) and Solarworld (Germany and USA).

THE PHOTOVOLTAIC MANUFACTURING CONSORTIUM

Based on economic and population growth, it is predicted that energy demand is going to triple in next 100 years. The percentage of U.S. electricity produced by non-hydro renewable energy sources is expected to increase from 4% in 2009 to 12.3% in 2030. As a result of these predictions, the investments in PV industry tripled the last years while the renewable energy sources will grow nearly 207% by 2030.

In response to the market trends in photovoltaics for low cost energy production and the focus given in thin film solar cells, the US Department of Energy, as part of the SunShot Initiative, awarded to CNSE and International SEMATECH, the Photovoltaic Manufacturing Consortium (PVMC) initiative. The PVMC is based in Albany, New York, at the CNSE-University at Albany campus. It is an industry led consortium with cooperative R&D programs among industry, university, and government partners. Its overall goal is to work on innovative solar technologies, pulling research into the industry mainstream, lead major programs to address critical industry transitions and focus manufacturing processes. More specifically during the first years of operation its goal is to accelerate the development, commercialization, and manufacturing of photovoltaic systems based on thin film CIGS (Haldar, 2011).

PVMC's goal is to improve absorber uniformity and increase the power conversion efficiency of CIGS thin film PV technologies in large deposition areas by improving manufacturing processes and driving down costs. The key components of PVMC include: collaborative R&D programs to address infrastructure needs in CIGS technology

and manufacturing; manufacturing development facilities to speed development and scale-up of CIGS materials, processes, equipment, facilities, and products; CIGS roadmap and standards to align industry research, development, and manufacturing; on line metrology and new characterization techniques; support to the industry in testing and reliability, balance of system, technology commercialization, and workforce development.

PVMC is expected to provide significant impact on the growth of the U.S. PV industry especially on CIGS based devices. The resources of PVMC, in addition to SEMATECH and CNSE, which are the founding members, include over 80 industrial partners and organizations, and over \$300 million in projected state, federal, and industry funds. More specifically, PVMC partners include the entire supply chain. These are organizations and companies representing universities and national laboratories, equipment, materials and metrology suppliers, module producers and integrators, and end users.

PVMC is establishing an innovative model similar to the one already in place at CNSE for the semiconductor industry. It is expected, within the next five years, to develop and commercialize CIGS thin film technology to increase power conversion efficiency and reliability of large area panels while reducing the cost of manufacturing. The focus of PVMC will initially be on reel-to-reel processing on flexible and light weight substrates. This unique effort is based on the collaboration and expertise of SEMATECH's industry consortium model and CNSE's public-private partnerships and state of the art infrastructure. The PVMC partners are providing the expertise, experience, and knowledge needed to help the industry move toward PV optimization and commercialization faster. To promote this integration and collaboration of key players from across the spectrum of the PV industry with CNSE and SEMATECH,

In addition to these activities, PVMC has established technology working groups of experts to produce and publish the International Technology Roadmap for PV (ITRS PV) in order to assess the industry's future technology requirements. In fashion similar to the one expressed by the International Technology Roadmap for semiconductors, these future needs for PVs are expected to drive strategies for world-wide research and development among manufacturers' research facilities, universities, and national labs. The first ITRS PV is expected to contain the most recent information from the technology experts. The ITRS is a set of documents produced by a group of PV experts from the US PV industry and National Laboratories. The final documents to be published will probably carry the disclaimer, similar to the one for semiconductors: "The ITRS is devised and intended for technology assessment only and is without regard to any commercial considerations pertaining to individual products or equipment (www.itrs.net).

In addition to the PVMC there many other national and international organizations and government agencies to promote PV related activities such as research, R&D, manufacturing, market development and organizes various kinds of events. The SEMI PV Group is a global trade association which helps improvement of PV manufacturing standards and connects the PV supply chain. The group promotes the interests of its members on global issues, legislation, and critical regulations that facilitate PV supply chain interactions, innovation, promote investment, and grow the solar market. PV SEMI helps the PV manufacturing supply chain with an international network of trade events, listed in Appendix A, standards development activities, public policy initiatives, research, and information that work together to expand opportunities in solar energy for the group members and advance the industry overall.

CONCLUSION

As the worldwide interest in renewable energy is expected to increase, there is a growing demand for the development of photovoltaic devices that are produced at lower cost and offer higher performance than those commercially available today. In addition, certain characteristics such as light-weight photovoltaic modules and solar cells that can be fabricated on flexible substrates are of great importance for emerging applications. Thin-film photovoltaic solar cells have shown promise for enhancing the performance to cost ratio. Reducing fabrication and material costs will be essential for the broad deployment of solar cells.

On this market climate, thinner Si wafers, thin films and/or new architectures are expected to be the dominant technologies that will lead to improvements in efficiency and gain the largest market share. In addition to improving efficiency they offer the potential for lower areal manufacturing costs. CIGS based thin film photovoltaics are promising devices which could potentially gain a large market share which is currently dominated by silicon. US based manufacturers have the potential to gain a large market share by investing in development and fabrication and production of CIGS technology. The costs of solar power can essentially be covered in two ways: either by improving cell or module efficiency, or by reducing production and mounting costs. It is not clear yet, which CIGS technology dominate. Vacuum techniques such as magnetron sputtering and thermal evaporation are promising due to high efficiency performance reported (19.9%) and reproducibility. However suffer from large initial investment cost to purchase vacuum tools for large areas, the tools available are custom made and scaling-up for a large-manufacturing system is very difficult because of their complexity. Non-vacuum techniques are also promising as low cost deposition techniques. However, they suffer from low efficiency (~10%) on small

area devices while the large volume of chemicals disposal remains a problem.

The PVMC established by CNSE and International SEMATECH at the University at Albany is a significant effort to promote research and development and manufacturing in thin film technology in the US and also produce and publish the first ITRS in PV.

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KEY TERMS AND DEFINITIONS

CIGS: Copper indium gallium (di)selenide, is a compound semiconductor material that shows promise for use in manufacturing next generation thin-film photovoltaic solar cells.

Evaporation: Is a technique commonly used in thin film deposition. The source materials are thermally evaporated in a vacuum chamber and condense on a substrate.

Photovoltaic Manufacturing Consortium (PVMC): An industry led consortium with cooperative R&D programs among industry, university,

and government partners. It is organized by The College of Nanoscale Science and Engineering (CNSE) at the University at Albany and the International SEMATECH.

Solar Cells: Are solid state devices that convert photon energy (the energy of light) into electricity by the photovoltaic effect.

Thin Films: Are thin layers of material(s), ranging from a few Angstroms to several micrometers in thickness, deposited on a substrate. They are used extensively in semiconductor devices and optical coatings.

APPENDIX

The authors would like to conclude the chapter with a series of global solar events organized by the SEMI PV Group: PV Fab Managers Forum (www.pvgroup.org/pvfmf), PV Production & Technology, Intersolar Europe (www.pvgroup.org/events/ctr_032929), Intersolar North America (www.intersolar.us), North American PV Fab Managers Forum (www.semiconwest.org/SessionsEvents/Photovoltaic), PVTaiwan (www.pvtaiwan.com), SOLARCON India (www.solarconindia.org), PVJapan (www.pvjapan.org), SOLARCON China (www.solarconchina.org).

Chapter 8

Nanoparticle Scattering, Absorption, and Interface Effects for Surface Plasmon Enhanced Thin Silicon Solar Cells: Theory, Past Findings, and Future Directions

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ABSTRACT

Recently, surface plasmons have been employed in a variety of methods to increase the efficiency of solar cells. Surface plasmons are oscillations of electrons that arise from surface effects of light interaction with materials that have appreciable free carrier densities; their resonance is confined to a region that depends on the dielectric response of the medium. It has been observed that noble metals exhibit this resonance within visible- near IR range, making them an attractive candidate for silicon solar cells whose primary absorption bands are in this region. Research in silicon-based plasmonic solar cells has utilized the high scattering cross section and favorable angular distributions of noble metal nanoparticle-scattered radiation to increase absorption of thin silicon devices, which are normally weakly absorbing for photons of energy below 2 eV. The interaction is subject to interface effects, interferences of scattered and incident radiation, and the dielectric nature of the embedding medium or surface. In addition, perturbations caused by the longitudinal field of the metal nanoparticle may theoretically enhance the direct interband transitions of free carriers near the particle surface, further enhancing the photocurrent. This latter possibility has yet to be fully explored experimentally in crystalline silicon photovoltaics.

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INTRODUCTION

Thin Film Crystalline Silicon Solar Cells

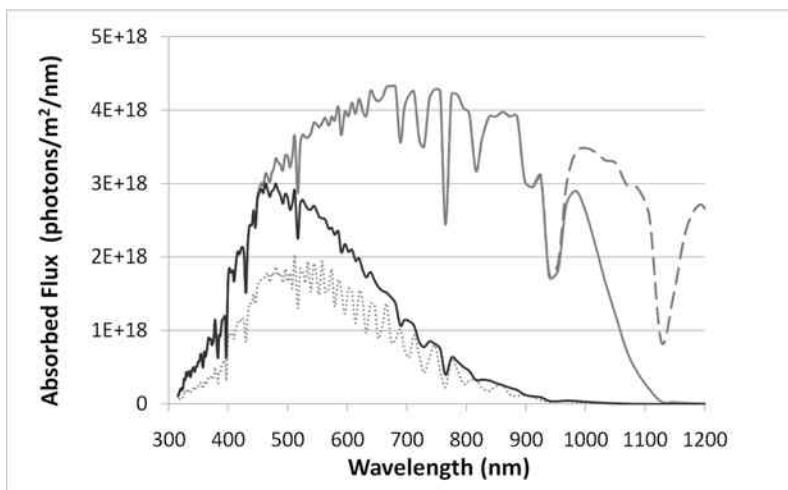
Silicon is the second most abundant material in the earth's crust. It accounts for the vast majority of electronic devices and lies at the heart of the computer industry. Despite its being abundant, environmentally benign, and at this point in our scientific evolution precisely grown and engineered, it is—to put it somewhat poetically—not particularly fond of our sun's offerings. Its absorption coefficient in much of the solar spectrum is so weak that crystalline substrates 300 micrometers thick are required to adequately absorb the bulk of photons whose energy is greater than or equal to its bandgap. Though a thickness less than third of a millimeter may seem nominal by everyday standards, it has in fact proven to be a central factor compromising the adoption of silicon photovoltaics. Semiconductors of direct bandgap materials require thicknesses of a few micrometers, expediting their production and

reducing their costs. As is seen in Figure 1, 300 μm of silicon with an adequate anti-reflective coating will absorb 90% of above bandgap photons, while a 2 μm c-Si film with no front or rear reflection absorbs only one third; for a film on a glass substrate without any anti-reflective coatings, that number drops to barely about one fifth.¹ Yet the long-term benefits of silicon cannot be understated: it is inexhaustible and nontoxic. For this reason, much of silicon-based photovoltaic research now focuses on methods of increased absorption and light trapping within silicon itself, so that thin crystalline silicon solar cells, less than a few micrometers thick, may attain efficiencies as high as bulk wafers.

Plasmonic Modes in Metal Nanoparticles

One path to achieving this is by harnessing plasmonic modes in metal nanostructures. The interaction of light with confined electron gases can lead to numerous remarkable phenomena, which due to dielectric-metal boundaries are ab-

Figure 1. Absorbed photon flux for 300 μm (upper solid line) and 2 μm (lower solid line) thick c-Si wafers, assuming no reflection on the front or rear of the cell. Also shown is the absorbed flux for a 2 μm c-Si film with no antireflective coatings situated upon on a glass substrate (dotted line), and the incident AM1.5 solar flux (dashed line).



sent in bulk metals. To gain some insight, let us begin with a look at the dielectric function of one metal which will receive considerable attention in the next few pages. Figure 2 shows the real and imaginary parts, ϵ' and ϵ'' , of the dielectric function of silver, along with the Drude free electron model of a Ag predicted on the basis of its electron density (Johnson & Christy, 1972). The primary plasma frequency, ω_p , occurs where ϵ' vanishes. Though the free electron model predicts a value of about 9.2 eV for ω_p , the influence of the ionic potential on the bound electrons lowers this value to 3.8 eV (Ehrenreich & Philipp, 1962). Below ω_p , the real part of ϵ tends further and further negative, associated with high reflectance and more pronounced electric field screening, and above ω_p , ϵ tends to 1 while the imaginary portion, ϵ'' exhibits a discrepancy with the free electron curve of a few eV, a result of interband transitions which are neglected in the free electron model. It is in the region immediately below ω_p that is of particular interest in metallic nanostructures. In a bulk metal, a strong resonant interaction occurs between the free electrons and the oscillation of the photon's electric field at ω_p , corresponding to the creation of bulk plasmons of energy $h\nu_p$. In a small sphere, a similar interaction occurs at the resonant frequency $\omega_{spr} = \omega_p / \sqrt{1 + 2\epsilon_m}$, which is somewhere below ω_p , in the region where ϵ_p is negative (Bohren & Huffman, 1983). The associated quantum particle is dubbed a "surface plasmon." While most solid materials with an appreciable free electron density exhibit the characteristic negative-to-positive transition of the real dielectric function about ω_p , the actual value of ω_p itself dictates the applicability of these materials for use in photovoltaics. As ω_p^2 is proportional to the free electron density, metals have much greater ω_p values than semiconductors: they are typically in the visible and UV range; thus the resonance condition, is satisfied within the solar spectrum. It is for this reason that they are of

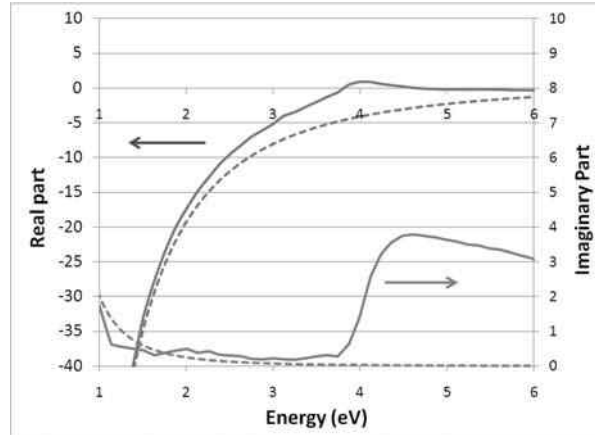
particular theoretical and experimental interest in photovoltaic devices (Bohren & Huffman, 1983).

Relevance of the Noble Metals

Of particular importance are the noble metals, Ag, Au, and Cu. The dielectric functions ϵ_p of Au and Ag are shown in Figure 3 (Cu closely mimics Au in this region and is omitted for clarity) (Johnson & Christy, 1972). Also shown are the plots of $-2\epsilon_m$, where ϵ_m is the dielectric function (real part only) of Si, SiO₂, or air. As will be described later, the Surface Plasmon resonance condition occurs when $\epsilon_p + 2\epsilon_m = 0$; the intersection of $-2\epsilon_m$ with ϵ_p indicates the Surface Plasmon frequencies when these metals are embedded as small spheres in the corresponding medium. Superimposed upon this graph is the solar spectrum (arbitrary units), and as can be seen, ω_{SPR} is for the noble metals near the region of high irradiance, and can be further tuned by altering the particle size and shape. For this reason, nanoparticle-based plasmonic photovoltaic research has focused almost exclusively in the noble metals, in particular Ag and Au.

In Figure 3, one notes that as ϵ_m increases, ω_{SPR} exhibits a clear redshift. For example, for Cu nanospheres in air, SiO₂, and Si, ω_{SPR} is 350, 450, and 750 nm, respectively. In this manner, the exact resonance frequency can be tuned by altering the dielectric environment, as has been indicated in previous work with Ag nanoparticles embedded in SiO₂, a-Si, c-Si and TiO₂ (Jensen, Malinksy, Haynes, & Van Duyne, 2000; Beck, Polman, & Catchpole, 2009; Mertens, Verhoeven, Polman, & Tichelaar, 2004; Lim, Mar, Matheu, Derkacs, & Yu, 2007; Liu, H. Wang, Li, & X. Wang, 1998). The plasmon resonance, both in peak location and width, can also be tuned with particle size and shape (Catchpole & Polman, 2008a; Stuart & Hall, 1998; Xu, Tazawa, Jin, Nakao, & Yoshimura, 2003; Kottmann, Martin, Smith, & Schultz, 2000). Due to these consider-

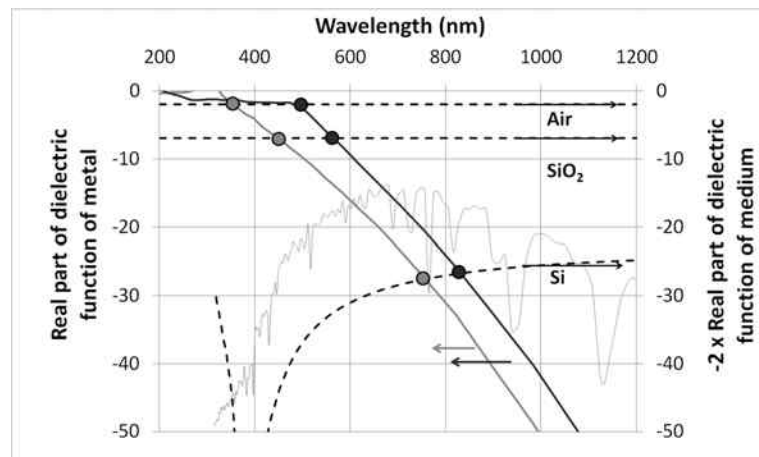
Figure 2. Real (left axis) and imaginary parts (right axis) of the dielectric function of Ag as a function of energy, taken from the Drude free electron model (dashed line) and experimental data (Johnson & Christy, 1972) (solid line).



ations, it is clear that the factors affecting the plasmon resonances are numerous and interconnected—indeed, with so many avenues of exploration, harnessing the remarkable properties of light incident upon metallic nanoparticles can provide for an incredible breadth of insightful

research. Let us now turn to a more in-depth investigation of the theory of a small dielectric or metal particle embedded in a uniform electric field, along with the two primary effects near the resonance: increased, preferential scattering and enhanced proximal electric fields.

Figure 3. Real part of the dielectric function (left axis) of Ag (leftmost solid line) and Au (rightmost solid line) as a function of wavelength; $-2 \cdot \epsilon_m$ (right axis) for air, SiO_2 , and c-Si (dashed lines). Superimposed is a normalized graph of the solar spectrum photon flux.



ENHANCED SCATTERING: MIE THEORY

Surface Plasmon Oscillations in Small Metallic Spheres: Basic Theory

Owing to design and materials considerations, typical nanoparticles will range in size from 10 to 200 nm in diameter. From a theoretical standpoint, the size is beneficial for two reasons. A 10 nm-diameter Ag sphere contains nearly 5000 atoms, so is large enough to exhibit the bulk properties of a crystal; in modeling, one generally assumes the bulk dielectric properties. In addition, a 100 nm sphere is a small fraction of the wavelength of visible light and IR light, whereby the incident electric field can be considered approximately uniform over the surface of the sphere. In determining the electric field distributions within and around the sphere, the exact solution requires that the incident field is assumed a plane wave, which is then expanded into a series of basis functions, the spherical vector harmonics. The coefficients of this expansion are determined by exploiting the orthogonality of the vector harmonics and integrating its product with the plane wave over all space, in the same way the coefficients of a Fourier series are determined. The coefficients are then given in closed form by matching the boundary conditions at the interface, with the radial portion given by Bessel functions and the angular portion by Legendre polynomials. Finally, an approximation to any desired accuracy can be determined by expanding these coefficients in increasingly higher powers of the size parameter, $\rho = kR$ ($k = 2\pi n/\lambda$ is the wavevector of the incoming light and R is the particle radius), a measure of the particle size in comparison to the wavelength. From these coefficients, the scattering distributions and intensities are derived. This more involved approach is described in full detail in the text by Bohren and Huffman (1983).

On the other hand, for the small particle approximation, only the lowest order term in this expansion is retained, giving the same result as that of a sphere within a uniform static electric field, an elementary calculation by comparison. The nanoparticle diameter is usually small enough that the uniform field approximation holds, with the next lowest order terms occasionally being added for better accuracy in larger particles. Let us expound this latter approach. The total electric field $E(r, \theta, \phi)$ outside a particle of a dielectric constant ϵ_p and radius R , embedded in a medium of dielectric constant ϵ_m and within a uniform applied electric field E_0 pointing in the z-direction is given by (Griffiths, 1999):

$$\mathbf{E} = E_0 \hat{\mathbf{z}} + \frac{R^3(\epsilon_p - \epsilon_m)E_0}{r^3(\epsilon_p + 2\epsilon_m)} (2 \cos \theta \hat{\mathbf{r}} + \sin \theta \hat{\boldsymbol{\theta}}) \quad (1)$$

This is identical to the superposition of two fields: the applied field and that of a point dipole, with dipole moment $\mathbf{p} = \alpha \epsilon_m E_0$ and polarizability

$$\alpha = 4\pi R^3 \frac{(\epsilon_p - \epsilon_m)}{(\epsilon_p + 2\epsilon_m)} \quad (2)$$

We call this the dipole or electrostatic approximation. It is clear that the scattered electric fields can become very large when $\epsilon_p + 2\epsilon_m = 0$, at the Surface Plasmon resonance, provided the imaginary part of ϵ_p is small, as is usually true. In this case, enhanced and directional scattering will occur. In the dipole approximation, the electric field can of course be taken to be that of an incident plane wave of arbitrary polarization and a wavelength sufficiently large enough for this approximation to hold. The dipole points in the direction of the electric field vector and oscillates in line with the electric field of the incident

photon, so for non-linearly polarized light it will change orientation over time. This is inconvenient for calculating the radiated power, which is much more easily determined when assuming a linear oscillation. Fortunately, any polarization state is a combination of linearly polarized radiation either parallel ($I_{\parallel}$) or perpendicular ($I_{\perp}$) to the scattering plane, which is defined by the direction of the incident light propagation and the direction of observation. Solar irradiation is unpolarized, and so it is in fact a direct average of these two states. For $I_{\parallel}$ states, the dipole is oriented at an angle θ_d to the direction of observation, and for $I_{\perp}$ states the dipole is always oriented at $\theta_d = 90^\circ$ to the direction of observation. Thus the time-averaged scattered radiation of an electric dipole of polarizability given by Equation 2, excited by unpolarized incident radiation of angular frequency ω is found to be (Jackson, 1962; Bohren & Huffman, 1983):

$$\mathbf{I}_s = \frac{\omega^4 n^5 R^6 I_i}{c^4 r^2} \left| \frac{\epsilon_p - \epsilon_m}{\epsilon_p + 2\epsilon_m} \right|^2 \frac{\cos^2 \theta + 1}{2} \hat{\mathbf{r}} \quad (3)$$

where $n = \sqrt{\epsilon_m}$ is the medium's refractive index, $\theta = \theta_d + \pi$ is the angle of observation relative to the direction of the incident radiation, and the intensity of the incident light is given by

$$I_i = \sqrt{\frac{\epsilon_m}{\mu_m}} \frac{E_0^2}{2} \quad (4)$$

Here the last factor in the scattered radiation accounts for averaging over both polarization states: $\sin^2(\theta_d) = \cos^2(\theta)$ for $I_{\perp}$ states and $\sin^2(\theta_d) = 1$ for $I_{\parallel}$ states. The angular portion indicates an important fact: the distribution of the scattered light is equal in the forward and ($-\pi/2 < \theta < \pi/2$) and backward ($\pi/2 < \theta < 3\pi/2$) directions. On the other hand, since the demonstration of enhanced photocurrent in photodetectors and solar cells rely on the preferential forward scattering of light, it is clear that the dipole approximation is inadequate

and higher order terms must play a role. As will be seen later, most situations in which intense light scattering is sought rely on nanoparticles whose diameters are 100 nm or more, that is for which p in the 400–1100 nm range is therefore greater than 0.5 and even as high as 4 for mediums of higher ϵ_m . In this regime, the dipole approximation does not hold and increased forward scattering may prevail. Indeed, for size parameters of this order, the proportion of light scattered in the forward direction may well be several times the fraction that is backscattered (Bohren & Huffman, 2003; Temple, Mahanama, Reehal, & Bagnall, 2009). Furthermore, when the particle is situated near an interface of two different dielectric media, the asymmetry is magnified, as will be discussed later.

The light interaction of a dielectric sphere with light is known as Mie theory, after one of its early investigators, Gustav Mie. Extensions to Mie theory may take into consideration different shapes, sizes, interparticle coupling, and quantum effects. These will not be developed in this paper, though an introduction to scattering from various shapes is given by Bohren and Huffman (1983) and a comprehensive overview of the interparticle effects for the case of Au nanoparticles is given by Ghosh and Pal (2007)). Ruppin (1975) describes the effect of longitudinal oscillations—that is, bulk plasmons—in small metal spheres, in addition to the typical electromagnetic transverse oscillations. The result of these is a number of smaller oscillations above the plasma frequency, although the appearance of these is minimal for particles of diameters above 20 nm. In addition, a considerable amount of theoretical work has been done in addressing the quantum effects in small nanoparticles (Ruppin, 1975; Rice, Schneider, & Strassler, 1973; Ruppin & Yatom, 1976; Lushnikov, Maksimenko, & Simonov, 1978; Wood & Ashcroft, 1982; Granqvist & Hunderi, 1977), although virtually all photovoltaic experimental and theoretical work has treated the physical interaction and the dielectric function—using bulk values along with effective medium averaging—as

a classical one. Considering the regime delineated by the wavelengths of the solar spectrum and the sizes of the nanoparticles, the classical picture is more than sufficient, especially when including size and shape effects in the modeling (Bohren & Huffman, 1983; Granqvist & Hunderi, 1977).

Extinction Cross Sections

A particle will both scatter and absorb light. The sum of these processes is often referred to as “extinction,” suggesting that either of these two processes lead to situations in which the intensity of the incident beam is diminished, either by the conversion of light to another form of energy, typically heat through damped electronic oscillations, or by changes in photon momentum. The total scattered cross section is defined as the ratio of the scattered flux, integrated over an enclosing surface, to that of the incident light intensity; it has dimensions of area and is therefore viewed as a “cross section” in much the same way as scattering in geometric optics and nuclear physics. In the dipole approximation, this is (Bohren & Huffman, 1983):

$$C_{sca} = \frac{3k^4}{2\pi} \left(\frac{4\pi R^3}{3} \right)^2 \left| \frac{\epsilon_p - \epsilon_m}{\epsilon_p + 2\epsilon_m} \right|^2 \quad (5)$$

while the total absorption cross section is

$$C_{abs} = 3k \left(\frac{4\pi R^3}{3} \right) \text{Im} \left(\frac{\epsilon_p - \epsilon_m}{\epsilon_p + 2\epsilon_m} \right) \quad (6)$$

It is seen that the absorption cross section is linear with particle volume, while the scattering cross section is proportional to the volume squared: absorption dominates scattering in very small particles and vice versa for larger ones. As expected, the imaginary part of the particle dielectric function dictates the absorption cross section (we assume that the medium is only weakly absorbent).

Mechanisms for Increased Absorption

What is the benefit of enhanced scattering, one may ask, if normally incident light is already directed in the forward direction toward the wafer? One simple answer is that forward scattering negates the effects of reflection, which increases for substrates of higher refractive index. A bare silicon wafer reflects more than 30% of the solar spectrum for normally incident light, and exploiting enhanced forward scattering provides an effective antireflective coating without damaging the surface as is done in the usual surface texturing techniques. This avoids the problem of increase surface recombination, a carrier collection limiting factor particularly in thinner cells (Brendel, 2003)

Secondly, scattering aids collection efficiency when the scattering directions are parallel or nearly parallel to the device surface, and especially when within the critical angle for total internal reflection. Considering the refractive indices of silicon—between 3.5 and 4 for 500-1000 nm light—the critical angles for total reflection within silicon upon air, SiO₂, and Si₃N₄ are 15, 24, and 30 degrees respectively. The benefit of this is that the path length within the wafer may increase several times, increasing the collection of low energy photons whose absorption lengths are larger than the device thickness. In addition, for thin device layers which can support a limited number of guiding modes, light is scattered strongly in directions corresponding to these guided modes. These modes can account for a sizeable portion of the scattered radiation within the semiconductor, in turn greatly increasing the likelihood of absorption (Catchpole & Pillai, 2006; Mertz, 2000).

Lastly, a quick look at Equations 5 and 6 suggests that the scattering and absorption efficiency are not limited to values between 0 and 1. In fact, rewriting these and taking the ratio to the geometrical cross section (πR^2 for a sphere), we obtain:

$$Q_{sca} = \frac{8\rho^4}{3} \left| \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + 2\varepsilon_m} \right|^2 = \frac{k^4}{6\pi^2 R^2} |\alpha|^2 \quad (7)$$

$$Q_{abs} = 4\rho \operatorname{Im} \left(\frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + 2\varepsilon_m} \right) = \frac{k}{\pi R^2} \operatorname{Im}(\alpha) \quad (8)$$

At the surface plasmon resonance, ε_p' equals $-2\varepsilon_m$, so the denominator of the scattering ratios is determined entirely by ε_p'' . For small values of ε_p'' , the sphere can become highly polarized, and in fact both Q_{abs} and Q_{sca} may be more than unity. The particle therefore actually interacts with light that is not geometrically incident on it. This implies that sparse coverage of nanoparticles on a surface may be sufficient to capture and scatter the majority of the incident light. This remarkable phenomenon was indicated, for example, by Catchpole and Polman (2008a), where it was shown that with appropriately chosen particle size and shape parameters, Q_{sca} may reach up to 14 for Ag nanocylinders. The benefit of sparser surface coverage lies not only in the ease of material processing, but also in the prevention of interparticle coupling effects which may degrade the resonance benefits.

INITIAL FINDINGS

Forward Scattering, Interface Effects, and Guided Modes

Increased photoresponse due to the presence of metal nanoparticles was initially demonstrated in Si p-n diodes by Stuart and Hall (1996). Here a thin 160 nm of Si atop a buried oxide was decorated with Ag, Au, and Cu nanoparticles by depositing a 10-15 nm film and annealing at a low temperature, which leads to the formation of metal islands by coalescence. Though not indicated in their work (no SEM or AFM images were shown), this typically results in flattened particles

of longest dimensions ~30-200 nm, in some cases spherical and ellipsoidal, and in other cases more amorphous. The photocurrent was measured as the wavelength of the incident monochromatic beam was swept from 400 to 1100 nm. A relative photocurrent enhancement of 3x, 5x, and 12x for Ag, Au, and Cu respectively, all occurring at a peak wavelength ~800 nm, was found in each case when compared to the control sample. The SPR wavelengths for Ag, Au, and Cu nanoparticles in air should occur at approximately 350, 480-510 and 365 nm, yet the actual photocurrent enhancements peak for all three samples is much higher. The authors attribute this to the fact that the nanoparticles sit upon a silicon substrate of markedly higher dielectric constant than air, red-shifting the resonance. The effective medium is therefore some average of air (1) and silicon (~4). In addition, while not mentioned in their work, the size and shape of the particles likely play a large role in the redshifting of the resonance, though the actual effect is unclear without SEM or AFM images to indicate the effect of these geometric factors. Due consideration is also given to the fact that the photocurrent enhancement is most likely due to surface plasmon coupling rather than anti-reflection effects as a result of surface roughening by the particles, as the enhancement is too dramatic and the peak too localized.

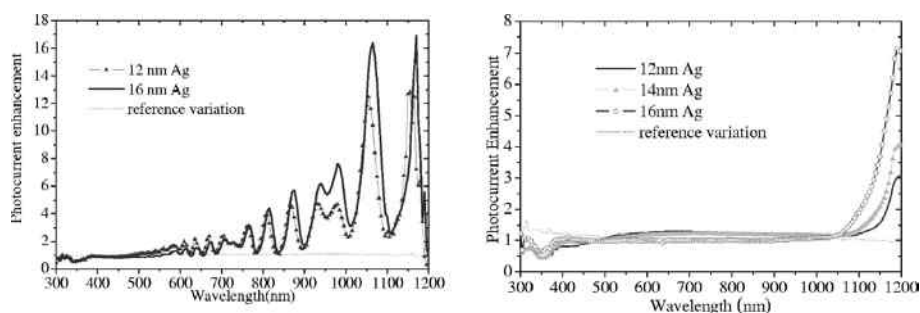
Similar trends and further extensions have been demonstrated in various studies published since Stuart and Hall's findings. Schaadt, Feng, and Yu (2005) performed a similar experiment, in which a bulk Si diode was suspended in a colloidal solution of Au nanoparticles, and photocurrent was measured. Here, SEM images show sparsely distributed nanoparticles upon the surface, of diameters 50, 80, or 100 nm. They observed a 1.4x-1.9x peak photocurrent enhancement, which broadens and shifts to higher wavelengths with increasing diameter as expected. Pillai, Catchpole, Trupke, and Green (2006) compared the photocurrent enhancement of bulk 300 um p-n junctions and 1250 nm SOI devices with Ag nanoparticles

of disperse size and density. The results, pictured in Figure 4 indicate that larger nanospheres exhibit higher enhancements, and that the enhancements of the thin SOI devices shows gains at wavelengths 600–1100 nm, whereas the wafer device exhibits these gains primarily in the vicinity of the band-gap where Si is weakly absorbent. As mentioned above, spheres with very small size parameters, when embedded in a uniform dielectric, do not show any preference for scattering in the forward versus backward direction. Forward scattering, however, increases rapidly with the size parameter and shows strong preference even with just a single term added beyond the dipole approximation (Bohren & Huffman, 1983; Born & Wolf, 1965). Temple et al. (2009) performed this calculation for a 100 nm Ag sphere in vacuum; they found non-preferential scattering for the dipolar mode at 393 nm and increased forward scattering—about 3 times versus the backward direction—for the quadropolar mode at 354 nm.

The situation is even more skewed for the case of particles located at the interface of two dielectrics. Such asymmetrical scattering was investigated by Lucosz and Kunz, (1977a; 1977b) and by Mertz (2000). The approach taken in the first paper relied on typical methods of determining electromagnetic fields in dielectric media utilizing Maxwell's equations and boundary conditions;

they derived the usual dipole radiated power distribution and integrated intensity as is found in any text on classical electrodynamics. The model was then extended by including the influence of reflection of the scattered field from a nearby interface, the result being that the interaction of the scattered and reflected waves may enhance or diminish the radiated power, with marked asymmetries at interfaces between media of different refractive indices. It was found that for point dipoles located at the interface of two materials of different dielectric functions, scattering is preferential into the denser medium. Using a more elegant argument based on the Lorentz reciprocity theorem, Mertz arrived at the same conclusion. Interestingly, the evanescent wave plays the primary role in transferring the power from the dipole to the denser medium: what is evanescent in one medium may be propagating in the second. These waves decay exponentially, and only in the case of very proximal dipoles will the fields—indeed nearly all of the radiated power—adequately couple into the denser medium. This asymmetry quickly diminishes for distances greater than the wavelength or so. This general trend is found for not just dipoles, but cylinders, spheres, and hemispheres as well (Catchpole & Polman, 2008a; Beck, Mokkaapati, Polman, & Catchpole, 2010).

Figure 4. Photocurrent enhancements for 1.25 μm SOI devices (left image) and wafer based devices (right images) with Ag nanoparticles, for varying thicknesses of deposited Ag. Reprinted with permission from Pillai et al. (2006).



Dipole Moment Phase and Interferences

Yet the preferential scattering into the material of higher dielectric does not tell the whole story: while the angular distribution is more favorable with decreasing particle-substrate distance, the total scattering cross section itself decreases, necessitating a trade-off when determining the proper dielectric spacer thickness. The cause of this reduced scattering and absorption cross section is the reduction of the effective driving field of the dipole itself. The phenomena described in the previous paragraph derive from the interference of scattered and reflected fields, and they assume that the dipole moment is unalterable. But since the dipole is the product of its polarizability and the driving field, then these would both have to be assumed isolated from the system, which is obviously not the case. The dipole can be classically modeled as a damped driven harmonic oscillator, whose frequency therefore matches that of the driving force (the incident field), and whose phase depends primarily on the difference of the driving frequency from the natural frequency. Being a sinusoidal quantity, it is certainly susceptible to the phase of other ambient radiation; that is, it will interfere with the incident wave (and this occurs without an interface) on the one hand, as well as with reflected waves from the nearby interface. To illustrate the first effect, let us look again at the dipole approximation for a dielectric sphere illuminated by a plane wave. Assuming that the particle is absorbing (so the dielectric function is complex), while the medium is not, we can rewrite the polarizability as a $|\alpha|e^{i\varphi}$ with the amplitude and phase given by:

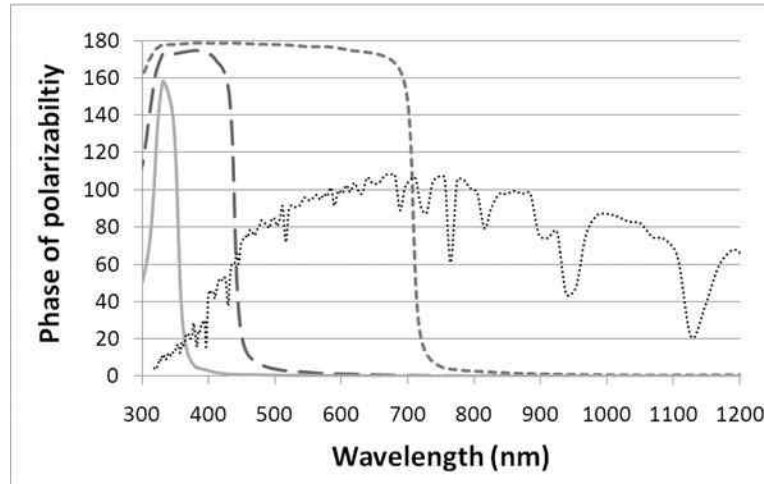
$$|\alpha| = 4\pi R^3 \frac{\sqrt{((\epsilon_p' - \epsilon_m)(\epsilon_p' + 2\epsilon_m) + \epsilon_p''^2)^2 + (3\epsilon_m\epsilon_p'')^2}}{(\epsilon_p' + 2\epsilon_m)^2 + \epsilon_p''^2} \quad (9)$$

$$\tan \varphi = \frac{3\epsilon_m\epsilon_p''}{(\epsilon_p' - \epsilon_m)(\epsilon_p' + 2\epsilon_m) + \epsilon_p''^2} \quad (10)$$

If the particle is absorbing, ϵ_p'' is nonzero, leading to a nonzero phase with the incident radiation. This is also evident in Equation 1 where it is seen that the total electric field is a superposition of the incident and dipole scattered radiation, and the phase of the second term, proportional to α , may reduce the overall field in particular directions. Dipole radiation scatters spherical waves, so the scattered field is not everywhere parallel to the incident plane wave. However, due to the $\cos^2\theta$ angular dependence of the scattered electric field, the components parallel to the incident wave are the largest. For these components, the scattered field can then be added to the incident field and the destructive or constructive behavior is determined by φ . The phase approaches π when the first term in the denominator is negative and large: this occurs in the region below the SPR wavelength, where $(\epsilon_p' + 2\epsilon_m)$ is positive and $(\epsilon_p' - \epsilon_m)$ is negative. On the other hand, above the SPR peak, the first term is large and positive, leading to a small phase. The situation becomes more skewed as ϵ_m is increased, as is shown in Figure 5. Thus, particularly in dielectric media, one would expect more interference effects for larger bandwidth regions in the solar spectrum, since the SPR peak redshifts.

Such detrimental effects have been observed by Lim et al. (2007). Here, experimental work was paired with FDTD simulations in determining the optical response of colloidal Au nanoparticles deposited on Si p-n junction photodiodes. While an enhanced response was found at a resonance position of 680 nm, a diminished response was observed at 500 nm, which is accounted for by the phase difference maximum of about 35 degrees in the Au polarizability near this point.

Figure 5. Phase of the polarizability for small Ag spheres embedded in air: $\epsilon = 1$ (solid line), SiO_2 : $\epsilon \sim 3.5$ (long-dashed line), and $c\text{-Si}$: $\epsilon \sim 11.9$ (short-dashed line)



Beck et al. (2009) also investigated these effects by coating bulk Si wafers with film stacks of different dielectric layers, with the top layer being either SiO_2 , or Si_3N_4 , or TiO_2 . On top of this, Ag hemispherical nanoparticles were fabricated using thermal deposition and low temperature annealing. It is found that in comparison to the reference sample, total absorption in the 600 to 1000 nm range decreases markedly for the TiO_2 sample, is comparable for the Si_3N_4 sample, and is enhanced for the SiO_2 sample. The SPR wavelength for the TiO_2 sample ($\epsilon_m \sim 6.5$) is sufficiently high that as discussed above, scattering for lower wavelengths has an appreciable phase, contributing to lesser absorption. The situation in Si_3N_4 is similar, though not as high: a slight decrease for 600-800 nm and a slight increase for 800-1000 nm. On the other hand, the SPR wavelength, being in the ~ 500 -600 nm range for Ag hemispheres on SiO_2 films on Si, is sufficiently low that constructive scattering dominates above 600 nm, leading to absorption of 80% - 90% for 600-1000 nm light, compared to 65% on the reference sample.

To remedy the effects of these interferences, one may alter the vertical placement of the nanoparticles with respect to the sample surface.

For example, by placing the nanoparticles further below the surface, one can ensure that high energy light will have been absorbed before impinging the nanoparticle. The particle may therefore act as an antenna for only those wavelengths whose absorption coefficients are sufficiently low enough, allowing an enhancement in this region while avoiding reflection of lower wavelength photons that lie in the $\phi \approx \pi$ range. Accordingly, it is found that if the Ag is placed on the backside of the sample, no diminution is seen in the 600-1000 nm range, while the absorption is increased in the 1000-1200 nm range, particularly in the TiO_2 sample whose resonance is closer to this range. Thus by placing the nanoparticles at the rear, the undesirable phase effects at lower wavelengths are eliminated, leaving only the increased scattering of higher wavelength photons. The result is that a rear-coated $\text{TiO}_2 + \text{Ag}$ nanoparticle solar cell exhibits an external quantum efficiency enhancement of more than two times in the Si bandgap range (Beck et al., 2009)

A second manifestation of polarizability phase differences arises when the dipole is placed very close to a dielectric or metal interface. Here, the reflected wave may be in and out of phase with the

incident wave, reducing or enhancing the driving field of the dipole moment as a periodic function of the dipole's distance from the interface (Lucosz & Kunz, 1977b; Catchpole & Polman, 2008b). Since the total scattered radiation is proportional to p^2 , which is itself proportional to the driving field squared, even slight changes in this field can have a pronounced impact. The reflected wave from an interface undergoes a 180 degree phase shift, meaning that the largest reduction in driving field will occur on the surface itself. To take an example, the refractive index of Si for 800 nm light is 3.7, whereby the amplitude of the transmitted wave is .43 times that of the incident wave. Due to the continuity of the tangential electric fields at the interface, this is the amplitude of the driving field at the surface, meaning a scattering cross section that is only $.43^2 \sim 20\%$ of that in the absence of an interface. However, for particles situated at 60, 100, and 200 nm above, the relative amplitudes will be .6, 1.2, and 1.5, or relative cross sections of .36, 1.4, and 2.3. Thus, particles very near the surface will experience diminished driving fields, while some slightly further away will experienced enhanced ones. As the usual fabrication geometry employs spheres or hemispheres upon the substrate proper, care must be taken to ensure that serious degradations do not occur.

The observations by Catchpole and Polman (2008a) and Hagglund, Zach, Petersson, and Kasemo (2008) offer lucid illustrations of phase effects that arise from the combination of the various scattered, reflected, and incident components. In the former, it was calculated that nanocylinders above a 10 nm SiO_2 underlayer on a Si substrate will scatter more than 85% of solar light into silicon but suffer a reduced scattering cross section compared to one placed a bit further above the substrate. This observation is corroborated in the latter. Here elliptical Au disks were patterned directly on a Si p-n junction and illuminated with several incident angles and polarization of monochromatic light. Compared to the unpatterned reference sample, the overall photocurrent was found to *decrease*

considerably in a wide neighborhood of the SPR resonance, for both polarizations and most incident angles. As expected, at the resonance, a strong field enhancement is found on the end of the disk nearest the Si, which is the denser medium. Yet due to phase differences, presumably between the transmitted and scattered fields, the actual scattered irradiation into the substrate is highly diminished in this region, which instead exhibits strong backscattering. When the cylinders were instead modeled with a small SiO_2 spacer beneath them, the resonance peak was highly blueshifted and the photocurrent enhancement was found to be similar to that of a sphere: enhanced above the main resonance and decreased below. Thus, the presence of the high-index substrate induces higher radiative coupling, which is nonetheless negated by interference with the outlying fields.

Rear Placement

These consequences arising from phase effects can to some extent be rectified by insertion of small dielectric films of refractive index somewhere between vacuum and silicon. Alternatively, one may place the particles on the rear of the cell as touched on above. The work by Beck et al. (2010) is a more in-depth study of the asymmetrical scattering effects in front versus rear placed cells. In a simple model, the authors calculate the effective dipole driving field of dipoles situation directly on a thin film SiO_2 atop a silicon substrate, by adding the incident and reflected electric fields in the case of varying SiO_2 thicknesses. For shorter wavelengths, the driving field is increased from 30% to 125% that of the incident field with a film thickness increase of 0 to 45 nm. As expected, the change is minimal for longer wavelengths, as the film thickness is too small to introduce appreciable phase differences. While not calculated in the paper, it can be shown that even for the case without the SiO_2 spacer, the driving field is very sensitive to the dipole's placement above the substrate. For example, if placed at the Si, the

driving field is modified by a factor of 0.3, while if placed 50 nm above the silicon, it is enhanced by a factor of 1.3, a simple manifestation of the modulation of the total wave amplitude $E_r + E_t$ in the upper medium over time.

Most interestingly, for rear-placed particles, the authors consistently find high scattering cross sections in the absence of a dielectric spacer; such cross sections decrease as the oxide thickness increases to $\sim$ tens of nanometers. This is further investigated in (Ouyang et al., 2010). Here, Ag nanoparticles were fabricated in one of two schemes: directly on the rear of a crystallized 2- μ m a-Si solar cell device, or similarly fabricated but with a 30 nm SiO_2 spacer between the Ag and the Si. Also, the authors tested similar schemes in combination with white paint for added scattering. External quantum efficiencies peaked in the region of 1100-1200 nm, and the highest enhancement (6x) was seen for the cell in which the nanoparticles were placed directly on the Si backside without the dielectric spacer. For the cell with the SiO_2 spacer, a 3x enhancement was observed, the same as applying white paint to the back of cell. The enhanced photocurrent for particles directly on silicon is attributed to more effective coupling of the near field into the silicon. By the same token, the detrimental phase effects that appeared in the other schemes do not arise. This can be understood in the following way. Since an anti-reflection coating was applied to the front of the cells, we may expect a decrease in the wave amplitude by approximately $\sqrt{(n_{\text{air}}/n_{\text{Si}})} \sim 0.5$ during transmission from air to the higher index substrate (with an associated increase in wavevector by a factor of n_{Si} to conserve energy and momentum). On the backside, the wave is partially reflected from the surface, but due to lowering of n from Si to air, the transmitted amplitude will be larger than that in Si by a factor a little smaller than $\sqrt{(n_{\text{Si}}/n_{\text{air}})} = 1.9$, say ~ 1.5 (due to some absorption). Thus, the total transmitted amplitude will acquire

a factor of 0.8 or so, a far cry from that previous case in which the interferences of reflected and transmitted waves give changes lower than 0.3. Moreover, since the transmitted wave amplitude does not interfere with any reflected waves, then unlike the case above the substrate, the amplitude is independent of the dipole placement above the substrate. Consequently, resistant to the phase effects that characterized the particles on top of the device, the scattered light from rear-placed particles can couple effectively into the higher-index medium, without exhibiting sensitivity to the distance from the interface.

The need to place the Ag nanoparticles upon the silicon directly, rather than upon a dielectric, passivating layer, complicates matters somewhat. It is true that as is claimed by Ouyang et al. (2010), for amorphous silicon and thermally crystallized poly-Si of small grains, the bulk minority carrier lifetime is so short that surface recombination plays a purportedly minimal role. The authors find that varying the surface recombination velocity from negligible to very high (10^7 cm/s) in their simulations does not change the efficiency of the devices beyond 1%. This is further corroborated by their experimental findings. However, it also puts into question the applicability of this process to more commercially viable and higher efficiency devices, which exhibit larger grains and thus longer bulk carrier diffusion lengths, ideally at least a few times the device thickness. In such cases, surface recombination is a major limiting factor; if the Ag nanoparticles are indeed to act as an effective light coupling mechanism upon a substrate whose bulk properties are so deficient as to render the surface effects unimportant, then there may be really little advantage over using a traditional surface texturing method whose depths are limited to about 1 μ m (Kadakia, Naczas, Bakhru, & Huang, 2010; Nishioka, Horita, Ohdaira, & Matsumara, 2008). A scheme in which noble metal nanoparticles are fabricated directly on the active silicon layer will

likely require an additional method to passivate the surface without compromising the proximity of the evanescent surface waves to the silicon.

ENHANCED FREE CARRIER INTERBAND TRANSITION RATES

Photocurrent Enhancements via Increased Transition Rates

Aside from tuning the cross section and angular distribution of particle-scattered light, a slightly different mechanism may be employed to increase the photocurrent in semiconductor p-n junctions. This is predicated on the considerable dipole moment of a nanoparticle about the surface plasmon resonance frequency. At this frequency the amplitude of the polarizability can be written:

$$|\alpha| = 4\pi R^3 \frac{\sqrt{\varepsilon_p''^4 + 9(\varepsilon_p'' \varepsilon_m'')^2}}{\varepsilon_p''^2} \approx 12\pi R^3 \frac{\varepsilon_m''}{\varepsilon_p''} \quad (11)$$

We see that for small values of the imaginary part of the dielectric coefficient of the particle, the polarizability, and hence the dipole moment, can be very large. The imaginary part provides a sort of measure on both the upper bound of the resonance and the width of the peak. As ε_p'' goes to zero, this peak becomes sharper and higher.

The scattered field of an oscillating dipole contains three terms, proportional to $1/r$, $1/r^2$, and $1/r^3$. The last of these is a spherical wave that accounts for the radiation described thus far. On the other hand, the first two terms account for scattered fields that are nonradiative, in the sense that E , H , and k , are not mutually perpendicular. Very close to the surface, the $1/r^3$ term dominates. This term is in fact, identical to the field of a *static* electric dipole whose dipole moment amplitude increases and decreases with the frequency of exciting radiation. Unlike the

scattered fields, here the energy stored in the fields is localized to the nanoparticle vicinity, which in this sense acts as a sort of energy antenna. Unlike radiation, it is a longitudinal field, and may cause electronic transitions at higher rates than are found for photons using typical Fermi golden rule calculations involving the Hamiltonian of free radiation. Instead, carriers may be created by a Hamiltonian of longitudinal oscillations. We will refer to this phenomenon of increasing transition amplitudes from one quantum state to another as *direct carrier generation*, in contrast to enhanced scattering, which is primarily a light trapping and guiding effect.

Initial Theoretical and Numerical Calculations

Historically, the use of direct carrier generation for photovoltaic applications has been examined primarily in organic solar cells, since nanoparticles can be more naturally embedded and fabricated in organic absorbing media (Rand, Peumans, & Forrest, 2004; S.-S. Kim, Na, Jo, D.-Y. Kim, & Nah, 2008; Westphalen, Kreibig, Rostalski, Luth, & Meissner, 2005; Morfa, Rowlen, Reilly, Romero, & Van de Lagemaat, 2008; Kume, Hayashi, Ohkuma, & Yamamoto, 1995). Some work, however, has begun in solid state p-n junction based photovoltaics. The theoretical examination is found in the papers, one by Luque, Marti, Mendes, and Tobias (2008) and the other by Kirkengen, Bergli, and Galperin (2007). In the first, a semiclassical approach is used to find the carrier transition enhancement using classically modeled fields and a first order harmonic perturbation given by Fermi's golden rule. The Hamiltonian of the perturbation is treated simply as the potential of the dipole moment in the metal nanoparticle: a longitudinal field whose amplitude is the product of the driving field and the polarizability. For metal spheres, a peak is obtained where the real part of ε_p equals $-2\varepsilon_m$; the approach given here is more general and uses elliptical particles. The dipole potential is

the product of the polarizability and a geometric factor that depends on the relative dimensions of the ellipsoid. The normalized absorption enhancement is then found to be

$$D = |\Lambda(\lambda)\Psi(\xi)|^2 \quad (12)$$

where $\Lambda(\lambda)$ is the polarizability at the wavelength λ and Ψ is a geometric factor associated with the relative dimensions of the ellipse as a function at the ellipsoidal coordinate ξ . As seen in Figure 6, the total enhancement resonance peak maximum and width is highly shape and medium dependent.² In Figure 7 is a graph of Ψ as a function of distance from the nanoparticle surface for various shapes, normalized to the enhancement at the particle surface. The x-axis is in multiples of the largest semiaxis of the ellipsoid. Within one or two factors of this length, the enhancement diminishes to less than 10% of the surface value; the need to place the particles directly near the photoactive medium is evident.

Further work examining the possibility of exploiting direct near-field carrier generation in carrier substrates has been done by Kirkengen, et al. Here the approach is quantum-mechanical, relying on the electromagnetic interaction Hamiltonian (Shankar, 1994) and the potential of an

oscillating dipole, the tight-binding approximation to characterize the states, and the transition rate again given by Fermi's golden rule. The direct absorption of radiation in the near field is found to have the same x^2 dependence on energy as typical indirect absorption (Yu & Cardona, 2005). Heating, radiation, and direct carrier generation are all found to be proportional to the dipole moment squared, so their relative magnitudes were compared. The central findings are that radiated power dominates at large distances, while direct carrier absorption through the dipole interaction dominates at smaller distances. Heating losses were calculated using a simple $P = I^2 R$ for an oscillatory dipole argument, where $I = qv/V = \omega qd/V = \omega p/V$, whereby heating is proportional to $1/V$ and thus dominates at very small particle radii. It was therefore recommended that any particles utilizing this interaction be placed in the close vicinity of the semiconductor, especially near the p-n junction, but are not so small that ohmic losses dominate.

Minority Carrier Lifetime Considerations

These two papers, and to some extent, Ouyang et al. (2010), make a compelling case for the fabrication of embedded noble metal nanopar-

Figure 6. Left image: Absorption enhancement (D , equation 16) for spheres embedded in air (solid line), SiO_2 (long-dashed line), and c-Si (short-dashed line) as a function of wavelength. Right image: absorption enhancement for ellipsoidal particles whose relative dimensions along the H , k , and E directions of the incoming photons is 10:10:1, for the same dielectric media.

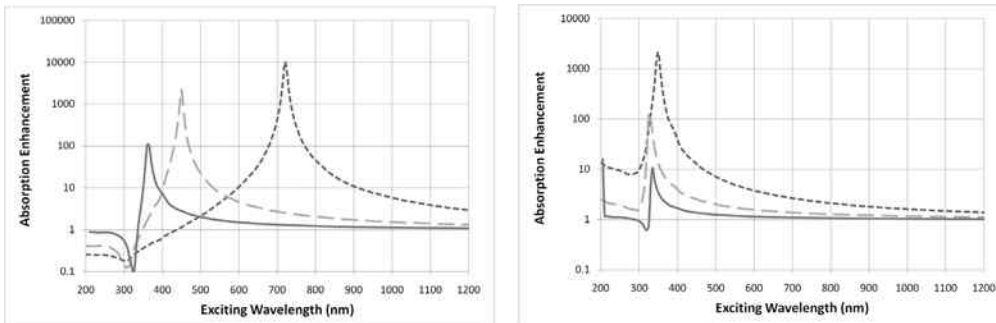
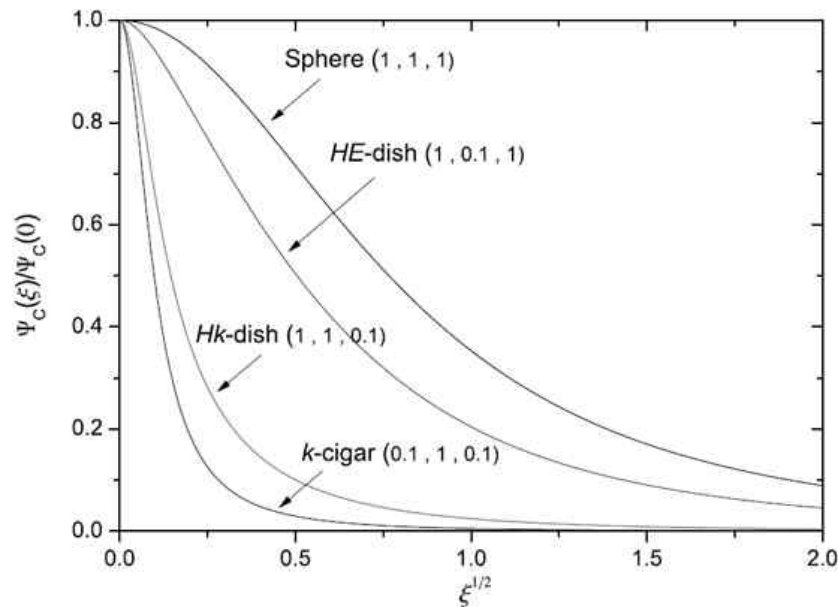


Figure 7. Magnitude of Ψ as a function of distance from nanoparticle surface, for various shapes whose relative dimensions along the H, k, and E directions, respectively, are given in parentheses. The graphs are normalized to the value of Ψ at the surface of the nanoparticle. Reprinted with permission from Luque et al. (2008).



ticles in silicon. But what will the incorporation of transition metal impurities have on overall performance, particularly when such impurities are known to have damaging consequences for carrier lifetimes? Typical bulk lifetimes of lightly p-doped CZ-Si range anywhere from 100 to 1000 μs , corresponding to diffusion lengths of 500 to 2000 μm . Intentionally contaminated Cu can degrade lifetimes by 10 times in p-Si and up to 100 times in n-Si (Istratov & Weber, 1998). For severe contamination, in which Cu can exist in concentrations of more than 10^{18} , the lifetime has been shown to dip to around 7 μs , or 100 μm (Zhong & Shimura, 1992). Nevertheless, for thin solar cells of thicknesses less than 10 μm , this is not expected to cause any degradation in photocurrent, being several times the device thickness. Sparse literature is found for Ag precipitates in Si, as it is not does typically exist in notable concentrations in solar grade silicon, unlike Cu and even Au. In one study (Adegboyega, Passari, Buttri, Poggi,

& Suzi, 1996) the lifetime of a FZ b-doped Si wafer was found to drop from 20 μs to 1 μs with a heavy treatment of Ag contamination. With further anneals at lower temperatures, the atomic Ag forms less electrically active precipitates and the lifetime recovers slightly to around 1 μs , which in p-Si corresponds to a diffusion length of 30 μm . It is somewhat unlikely that the reference sample would have such a low lifetime (one would expect it to be at least an order of magnitude higher, particularly for FZ Si), but the relative drop—3 orders of magnitude—suggests an effective capture cross section for Ag contaminants in Si. Still, even the worst case, a 1 μs diffusion length would be adequate for a device layer of less than 10 μm , as it is still 3 times the device thickness.

Due to its low absorption losses and high scattering cross sections, Ag nanoparticles are best suited for surface plasmon excitations in Si-based solar cells. When in precipitate form, they are less electrically active and contribute less to

recombination activity than in atomic states (Adegboyega et al., 1996). In addition, they exhibit more favorable absorption coefficients than either Au or Cu. Unlike Cu, Ag does not form silicides and is not mobile in Si at room temperature, which for Cu can lead to outdiffusion after just a few days (Istratov & Weber, 1998). For photovoltaic cells that would rely on the near-field coupling transition rate mechanism, these are important considerations, although more work is needed, particularly in assessing the relative enhancements and degradation due to optical absorption and recombination, respectively.

CONCLUSION

The mechanisms through which enhanced scattering cross sections, angular light scattering, and direct carrier absorption in small metallic particles are remarkable yet nuanced. As we have seen, light scattering from metallic particles may be greatly enhanced or entirely diminished; it may be very sensitive to particle environment, size, and shape, and may be guided almost entirely into only a few directions within a substrate. The surface plasmon resonance wavelength regimes for the noble metals are favorable for capture and scattering of solar irradiation, and there remains a great deal of potential for enhancement by exploiting enhanced transition rates, leading to higher direct carrier generation near nanoparticle surfaces; yet it is certain that, as with the phase effects of scattered light, tradeoffs between various enhancing and degrading mechanisms will need to be considered. The interplay of the competing phenomena imply that tuning the surface plasmon resonances and scattering cross sections through nanoparticle size, environment, placement, orientation, density, and composition is no simple task, as the wealth of literature in plasmonic engineering for photovoltaics reveals.

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KEY TERMS AND DEFINITIONS

Crystal: A material in which the atoms are arranged in a periodic structure in all three spatial directions on length scales spanning at least several times (and often tens of orders of magnitude) of the period itself.

Electric Dipole: A configuration of equal negative and positive charge densities, spatially separated, whose moment is equal to the separation distance times the positive charge density.

Noble Metal: In physics, refers to copper, silver, and gold, whose d-bands are filled but outer s-shells are only half filled, giving rise to distinctive optical and electronic properties.

Photovoltaics: The method of generating power from the sun's radiative energy through the use of solar cells.

Plasmonics: The field concerning the utilization of plasmons, in particular surface plasmons, for electronic applications.

Silicon: The fourteenth element of the periodic table, a semiconductor of bandgap 1.1 eV, and a ubiquitous material in the electronic industry.

Solar Cell: A solid state or organic device which converts the sun's radiation into electrical energy.

Surface Plasmon: An quantized oscillation of electrons on the interface between two different dielectric media.

Thin Film: A layer of material ranging from less than a nanometer to several micrometers in thickness, typically deposited or grown upon a substrate of much greater thickness, and used for a wide variety of electronic applications.

ENDNOTES

¹ In this graph, the total flux per wavelength (photons per area per unit wavelength) is shown, rather than the spectral irradiance (power per area per wavelength) as is done in some publications. The reason is that a single junction cell extracts photons of various energies at only one operating voltage, V_{mp} ; since a 1 eV and a 3 eV photon both deliver the same energy, qV_{mp} , only the number of absorbed photons is relevant. For a tandem solar cell, this would not be the case.

² The results obtained in the paper are replotted using the formulae given by Luque et al. (2008) for the embedding mediums of air, SiO_2 , and silicon (using a constant value of $\epsilon_m = 11.75$ for Si) and using the data for ϵ_{Ag} given by Johnson and Christy (1972). The discrepancy between this data and the published graphs originates from the deviations between the measured values of ϵ_{Ag} and the Drude free electron model used in their paper. Specifically, the imaginary part of ϵ_{Ag} is experimentally found to be much lower than the Drude model values, increasing the absorption enhancements by many factors.

Chapter 9

Nanotechnology and Polymer Solar Cells

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ABSTRACT

In response to environmental concerns there is a drive towards developing renewable, and cleaner, energy technologies. Solar cells, which harvest energy directly from sunlight, may satisfy future energy requirements, but photovoltaic devices are currently too expensive to compete with existing fossil fuel based technologies. Polymer solar cells, on the other hand, are cheaper to produce than conventional inorganic solar cells and can be processed at relatively low temperatures. Furthermore, polymer solar cells can be fabricated on surfaces of arbitrary shape and flexibility, paving the way to a range of novel applications. Therefore, polymer solar cells are likely to play an important role in addressing, at least in some small part, man's future energy needs. Here, the physics of polymer photovoltaics are reviewed, with particular emphasis on the computational tools which can be used to investigate these systems. In particular, the authors discuss the application of nanotechnology in self-assembling complex nanoscale structures which can be tailored to optimize photovoltaic performance. The role of computer simulations, in correlating these intricate structures with their performance, can not only reveal interesting new insights into current devices, but also elucidate potentially new systems with more optimized nanostructures.

INTRODUCTION

More energy is incident upon the Earth in one hour than is consumed by the world's population in an entire year. Harvesting just a small fraction of this solar energy could provide the solution to our long-term energy needs. However, first it is necessary for this solar energy to be captured, converted, and stored in a cost-effective fashion (Lewis, 2007).

Solar cells are a promising method of both capturing this energy, and converting it directly into electrical energy. While this still leaves the need for energy storage, in order to provide electrical power during times of darkness, there are still many benefits to using solar cells. Firstly, solar cells could be used to complement other technologies which do not rely on sunlight. For example, times of low sunlight and darkness often coincide

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with instances of high winds and rainfall which could provide wind and hydroelectric power, respectively (Hinrichs, 2006). Secondly, our current fossil-fuel based methods of generating energy are having a devastating impact on our environment. Ice sheet disintegration, sea level rise, and other adverse consequences of global warming, have recently emphasized our need for developing inexpensive alternative energy sources (Kerr, 2007). Furthermore, due to the portable nature of solar technology, these devices will especially benefit isolated communities in the developing world, whose fragile existence is most likely to be affected by global warming. However, the need for solar cells which can generate electricity as inexpensively as fossil-fuel based technologies are required before this energy source can provide a practical long-term alternative.

Solar cells based on silicon are currently the dominant photovoltaic technology. Silicon solar cells are reliable and highly efficient at converting solar energy into electrical energy. Combined with the natural abundance of silicon, this has made silicon solar cells a popular choice since the first p-n junction devices were fabricated in the 1950's (Cummerow, 1954). However, the high cost of silicon, especially crystalline silicon which is the most effective material, has limited the societal impact of solar cell technology and led to an interest in alternative materials (Shaheen, 2005). Thin film inorganic materials, such as amorphous silicon, have also attracted interest but high processing temperatures can make all inorganic solar cells prohibitively expensive. That said, recent advances in solar concentration could decrease the amount of solar cell material required and decrease the costs of silicon photovoltaics, while providing novel features such as partially transparency devices with non-planar geometries (Currie, 2008). In terms of photovoltaic research, however, there is still an impetus towards finding alternative materials and developing new devices.

In recent years, organic materials have emerged as a possible alternative to traditional inorganic

semiconductor solar cells. Organic photovoltaic cells are typically produced from either small-molecular-weight films or polymer films. One of the main advantages of organic materials is their high optical absorption which results in solar cell thicknesses on the order of 100nm; a thousand times thinner than silicon-based solar cell and ten times thinner than inorganic thin film cells (Kietzke, 2007). The use of organic materials can also significantly reduce the costs of production through solution processing and continuous deposition techniques. In other words, less of these cheaper materials can be deposited at lower temperatures and over relatively large areas. The cost of producing organic solar cells, therefore, is significantly less than inorganic cells. However, organic solar cells are inefficient at converting solar energy into electrical energy, with power conversion efficiencies reported to be only as high as 6.8% (Chen, 2009). This means that while the cost of polymer solar cells is small, their inefficiencies limit the "cost per watt" of these devices. In order for polymer solar cells to be economically viable the cost per watt of energy would have to be reduced, requiring an increase in efficiencies without driving up costs.

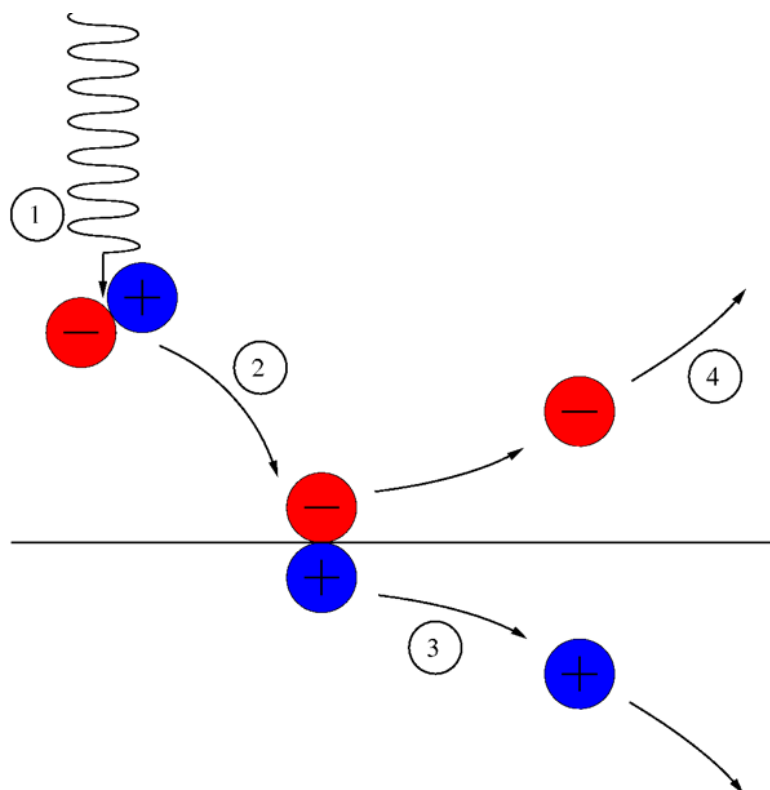
The overall efficiency of polymer solar cells is influenced by four main processes; the absorption of a photon to create an exciton (a mobile but bound electron-hole pair), the dissociation of an exciton to form a hole and an electron, the potential recombination of these charges, and the collection of carriers at their respective electrodes (Shaheen, 2005). In polymer solar cells the absorption of a photon does not result in free charge carriers, as in inorganic devices, but rather the creation of a coulombically bound electron hole pair, or exciton. This exciton must then find an interface between two materials with different electron donating and electron accepting properties in order for the exciton to be dissociated into a free electron and hole, on either side of the interface (Tang, 1986). These charges will then diffuse due to the density gradient at the interface, and drift

as a result of the built-in field from the difference between the electrode work functions, until the charges reach the electrodes. Free charges which successfully reach the electrodes can be extracted and contribute to the outside circuit. During this process the incident energy could be lost due to the polymer not absorbing incident photons, the geminate recombination of resultant electron-hole pairs or the recombination of separated electrons and holes prior to reaching the electrodes. To limit these losses, and consequently improve solar cell efficiencies, there is a need to discover better materials and further elucidate the device physics.

Conjugated polymer chains are an attractive option for organic devices, and can be regarded as quasi one-dimensional semiconductors. Both donor and acceptor polymers have been designed,

which preferentially transport holes or electrons, respectively. However, this is not necessarily a restriction on their actual ability to transport different charges but rather reflects the ease of charge injection from the electrodes; a material is often referred to as a hole, or electron, transporter when its ionization energy, or electron affinity, closely matches the Fermi level of the electrodes (Coropceanu 2007). A crucial aspect of organic materials are their low mobilities, which increases the likelihood of charge recombination, and energy loss, in organic solar cells. Efficient charge transport requires that the charges be able to hop from molecule to molecule and not be trapped or scattered. Therefore, charge mobility is dependent on pathways of high interchain charge-transfer rates, and disordered chain configurations play an im-

Figure 1. The mechanism of charge separation. Illustration of (1) photon absorption, (2) exciton diffusion to the DA interface, (3) dissociation of exciton into free charge, and (4) drift of free charge carriers to electrodes.



portant role (Athanasopoulos, 2007). More specifically, the mobility can depend on a variety of conditions including molecular packing, disorder, presence of impurities, molecular weight and temperature. The application of an electric field causes the charge carriers to drift and, in these disordered materials, also results in an increase in mobility with increasing applied field (Frenkel 1938). Increasing the mobility is necessary if the efficiencies of organic devices are to be increased significantly; the longer it takes for charge to leave the device, the greater the chance of charge recombination occurring.

Another crucial factor in organic solar cell performance is the creation of an exciton, rather than free charge carriers, upon absorption of a photon. An exciton is a mobile excited state that arises from the coulombic attraction between the electron and hole. In materials of low relative dielectric constant the photon creates an electron-hole pair which are bound together by their coulombic attraction. The exciton binding energy, which arises from this electrostatic interaction, is roughly an order of magnitude larger in organic materials than in inorganic materials (where thermal energy is enough to separate the photogenerated charges). In organic solar cells, therefore, photoexcitations result in the creation of excitons, whereas in inorganic devices photoexcitations typically lead directly to free carriers. In order for organic materials to function as photovoltaic devices the exciton must be dissociated (the electron and hole must be separated).

An efficient mechanism for dissociation is through the use of a donor-acceptor (DA) interface (Tang, 1986). A DA interface exists as the boundary between a donor and acceptor material. The donor material has a low ionization potential and the acceptor has a high electron affinity. When the exciton interacts with a DA interface it is energetically favorable for dissociation to occur, and for the electron to reside in the acceptor and the hole in the donor (Tang, 1986; Gunes, 2007). If the exciton does not interact with a DA

interface over a relatively short time scale then the electron-hole pair will undergo geminate recombination and the energy from the photon will be potentially lost. It is, therefore, imperative to photovoltaic performance that the DA interfaces are close to regions where photoexcitation occurs. Furthermore, upon dissociation the electrons and holes are now separated on either side of the DA interface and will have to travel in the different phases of a two-phase morphology in order to find their way to the correct electrodes. Even though the electrons and holes are confined to separate regions of the device, the charge carriers can still recombine at the DA interfaces in between the two phases. In particular, if the charges are unable to traverse the solar cell to the electrode, via a continuous path of the appropriate phase, then the concentration of charge carriers can build up at the interfaces resulting in an increase in charge recombination. Ensuring the charge carriers have a continuous pathway to the electrodes, therefore, is necessary for obtaining high photovoltaic efficiencies.

MORPHOLOGY

The three morphological constraints on the internal structure of polymer solar cells would appear to be, firstly, that the internal DA interface is always within a small distance from where photoexcitation occurs. Therefore, the diffusion distance of excitons, which is on the order of 10nm, limits the domain size of the internal morphology. Secondly, that the thickness of the polymer cell is sufficient to absorb the majority of incident light. While the optical absorption of polymers is generally high, and device thicknesses are smaller than that of inorganic devices, the thickness of polymer solar cells are still on the order of 100nm. Finally, that upon the dissociation of excitons, the resulting electrons and holes have direct access to the correct electrodes. In other words, as the electrons are confined to the acceptor material, and similarly

the holes are confined to the donor material, if the domains of these materials do not percolate then the electrons and holes will likely recombine before they can be extracted from the cell.

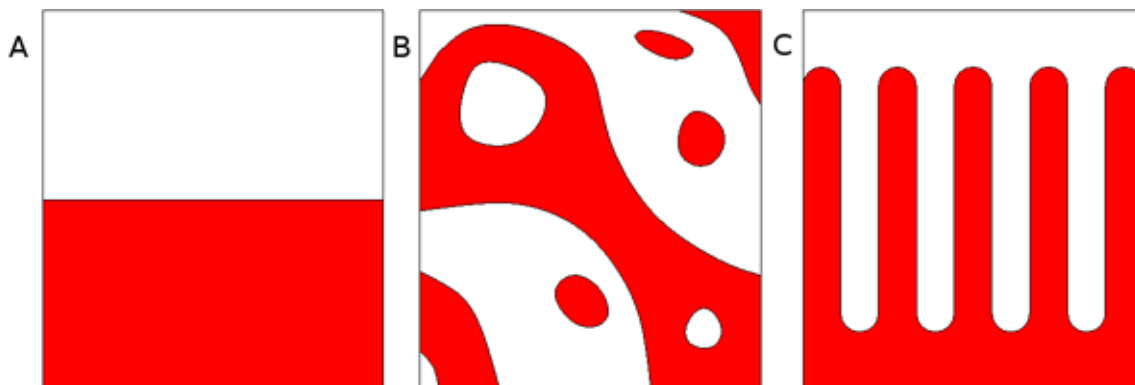
The simplest device morphology, as shown in Figure 2a, is the two-layer or bilayer solar cell. Introduced by Tang as a method of creating a DA interface through which charges can be separated, these structures are perhaps the simplest way to arrange two different materials (Tang, 1986). Either material can absorb a photon and the resultant exciton diffuses over a distance of roughly 10nm before either geminate recombination occurs or the exciton finds the DA interface. As the DA interface only exists through the center of the device, it is only excitons which are created in this narrow central region which will likely contribute to the external current. Excitons created in the remainder of the solar cell will recombine and the absorbed energy will be lost. For this reason bilayer devices are no longer considered practical for polymer solar cells, although it should be mentioned that if exciton diffusion could be improved then bilayer devices could become more practical. Improvements in molecular packing could increase exciton diffusion lengths and result in more of the excitons reaching, and being dissociated at, the DA interface (Rim, 2007). Furthermore, as the excitons are dissociated at the DA interface there exists a reduction in exciton concentration at the DA interface. The high concentrations of excitons within the donor and acceptor materials, and relatively low concentrations at the DA interface, results in an exciton concentration gradient. This concentration gradient results in the net drift of excitons towards the DA interface (Gregg, 2003).

In order to increase the efficiency of polymer solar cells, however, it is desirable to have the internal DA interfaces within close proximity to regions where photoexcitation occurs. Therefore, the two domains of the donor and acceptor materials can be blended together to form bulk-heterojunction solar cells (Yu, 1995; Yu, 1995b,

Halls, 1995). Typically, the two materials are spin-cast in a good solvent, resulting in thin films of phase-separated domains. An example of such a morphology is shown in Figure 2b and consists of random pathways in which the free charges can travel. Therefore, the excitons can find a DA interface within 10nm from where they are photoexcited, but the pathways in which the charges travel are tortuous and do not necessarily percolate. This can lead to morphological bottle-necks and cul-de-sacs down which the free charge can travel, without finding an electrode. Instead the charges will drift towards the DA interfaces and potentially recombine with opposite charges on the other side of the DA interface. This results in the loss of charge and, hence, a loss in converted energy (Buxton, 2006).

Alternatively, an idealized morphology has been proposed which would provide a domain size on the order of 10nm, allow for device thicknesses on the order of 100nm and provide continuous pathways for charge carriers to the electrodes (Coakley, 2003). This ideal morphology is depicted in Figure 2c and consists of an interdigitized structure where the donor and acceptor materials interlace in an organized manner. The most obvious way to create such morphologies in polymer systems is to use diblock copolymers. Diblock copolymers consist of two segments of different polymer species which are covalently bonded. This causes the polymer domains to phase separate only over a limited lengthscale, which depends on the length of the polymer chains. The idealized morphology was initially proposed by Coakley for hybrid devices, where diblock copolymer morphologies were used as a template for inorganic substitution. Alternatively, polymer brushes can be grown using surface-initiated polymerization to obtain similar structures (Snaith, 2005). However, the role of morphology is only part of the story. Polymer chain configuration and orientation can also play a crucial role in determining photovoltaic properties.

Figure 2. Different polymer solar cell morphologies: A) Bilayer; B) bulk-heterojunction, and C) idealized structures are compared



POLYMER CHAIN ORIENTATION

As mentioned previously, diblock copolymers are a good way to self-assemble the ideal morphology for polymer solar cells. There has, therefore, been a drive towards creating diblock copolymers where one segment of the chain consists of a donor material and the other segment consists of an acceptor material (Stalmach, 2000; Boer, 2001; Lindner, 2004). The photovoltaic efficiencies of diblock copolymer solar cells, however, have not shown any improvement over bulk-heterojunction solar cells. One possible reason for the disappointing performances is that the chain orientation inside the donor and acceptor domains is in the plane of the film. If the DA interface exists due to the microphase separation of the diblock copolymer, then it is well known that the chains will extend out perpendicularly from this interface. Hence, as charges traverse the device they are forced to hop inefficiently from one chain to the next.

Charge mobility in polymers is generally greatest along the backbone of a conjugated polymer chain and is significantly lower when charge transfer occurs between chains, and so any preferential orientation of polymer chains will result in anisotropic mobilities. As mentioned, this is just the case with diblock copolymer systems. The chains are oriented perpendicular to the

DA interface, which is beneficial to charge, and exciton, transport from the center of a domain to the DA interface but for charge transport within the domain this will result in very low mobilities and a greater chance of recombination. There is expected to be a competition between the transport of excitons from the center of the domains to the DA interface, and the transport of charge to the electrodes (Shah, 2009). If the polymer chains are aligned perpendicular to the DA interface (as in diblock copolymer systems) then exciton diffusion to the DA interface is enhanced, but charge transfer to the electrodes will be suppressed. If the polymer chains are oriented parallel to the DA interface, then the opposite is true, charge transfer to the electrodes will occur more readily at the expense of exciton diffusion to the DA interface. There is, therefore, likely to be some compromise between these two extremes. Perhaps with the chains oriented parallel to the DA interface in the center of the domains, and perpendicular to the DA interface near the DA interface.

The morphology and chain orientation of polymer solar cells can be modified through annealing and other processing methods. For example, thermal annealing of a bilayer solar cell can lead to donor and acceptor intermixing, and better power conversion efficiencies (Stevens, 2009). Electrical annealing, where the film is subject

to an external electric field during processing, is another method that has been explored. In organic light emitting diodes, devices have been found to exhibit superior properties subsequent to electrical annealing (Lee, 2000; Padinger, 2003). Although it is unclear in these experiments if the electric field oriented the morphology, creating stripes of different domains, or if the electric field oriented the polymer chains and enhanced the charge mobility. Either, or both, of these effects could also arise in electrically annealed polymer solar cells.

A common method of processing polymer blends is to spin coat them onto a substrate, together with a solvent, and allow the polymer blend to phase separate as the solvent evaporates. Interestingly, if the solvent evaporates quickly then an ordering front can occur within the phase separating film (Buxton, 2007). The layer of film nearest to the top will have less solvent (as the solvent evaporates from this surface) while nearer the substrate the solvent concentrations will be highest. Phase separation between the two polymers will occur at a critical solvent concentration, and this condition will be met at the top surface first. In particular, the top surface can phase separate before other regions of the film. As deeper regions of the film begin to phase separate they do so templated by the region of film directly above. This surface-induced phase separation can result in perfectly aligned domains perpendicular to the film (Buxton, 2007).

Processing can also promote molecular order in these films. Crystalline polymers can have higher mobilities, especially if the degree of crystallinity is high, and annealing can play a role in the degree of crystallinity in these materials. Recently, Schilinsky *et al.* (2005) and Sommer *et al.* (2009) have looked at the influence of molecular weight on crystalline polymer solar cells. In particular, they found that increasing the molecular weight of P3HT increased the crystallinity and improved hole carrier mobility by more than two orders of magnitude. Intermolecular order (stacking) is promoted in larger molecular weight polymers

and this, in turn, increases mobilities and device performance. As expected, similar effects have also been found for exciton diffusion lengths in crystalline polymers (Rim 2007). To enhance charge, and exciton, transport in polymer materials it may, therefore, be desirable to increase interpolymer ordering and crystallinity.

OPTICAL PROPERTIES

Of course, in optimizing the photovoltaic performance of polymer solar cells, it is worth remembering that the optical properties of these devices will also play a role. Recently, optical absorption enhancements have been reported through organizing the devices into regions of differing dielectric constants. These photonic crystals have been made from alternating layers of photoactive material and a low index of refraction conducting material, where the geometry was capable of enhancing spectral absorption by 17% (Tumbleston, 2009). Numerical calculations have also predicted this behavior in multicomponent polymer photocells (Shikler, 2007). In particular, it was found that both an energy flow from the less-absorbing to the more-absorbing material, and resonance amplification of absorption, lead to an enhancement in the numerically calculated absorption spectrum by up to 2.6 times (Shikler, 2007). This work emphasizes the role of scattering in these devices as a design tool to obtaining more efficient solar cells. Dielectric contrast can also be achieved by adding nanoparticles to polymer domains to create photonic crystals and this could be used to design, for example, DA regions of different dielectric constant (Buxton, 2003). With the DA domain size on the order of 10nm, and the domain spacing for dielectric contrast comparable to optical wavelengths, it may be interesting to consider the phase separation of two different semiconducting block copolymers.

While it is highly desirable to increase absorption through scattering, polymers typically absorb

only a small portion of the whole solar spectrum. It is, therefore, highly desirable to absorb a broader fraction of the incident solar spectrum using low-band gap polymers. Recently, for example, Wu *et al.* (2009) developed a new low band gap semiconducting polymer for polymer solar cells, which exhibited a power conversion efficiency of 5.6% (Wu, 2009). The incorporation of dye molecules could also increase absorption.

Since it seems unlikely that a single organic material can absorb efficiently over the entire range of the incident solar spectrum it is likely that tandem solar cells, or multijunction solar cells, will help push the performance of polymer solar cells. Tandem solar cells consist of two (or more) subcells which on their own would act as a solar cell. However, in tandem cells these subcells are combined one on top of the other, with the uppermost subcell absorbing higher energy photons and the lower subcells absorbing lower energy photons. One difficulty with tandem solar cells is that the total current from the device is limited by the lowest current-generating subcell. That said, tandem polymer solar cells have been constructed. Dennler *et al.* (2006) found that the open circuit voltage was nearly doubled in a P3HT:PCBM and ZnPc:C60 tandem solar cell, but that the power conversion efficiency was lower than a P3HT:PCBM cell alone. Recently Kim *et al.* (2007) reported tandem solar cells exceeding 6% conversion efficiency by using a TiO_x interlayer to separate two subcells. This tandem approach will likely be a necessary ingredient to polymer solar cell designs, if these devices are to harvest a broader fraction of incident sunlight. However, the success of tandem solar cells will depend on the development of novel low-bandgap materials.

HYBRID SOLAR CELLS

A promising route for maintaining the benefits of polymer solar cells, such as flexible devices and ease of production, whilst increasing device per-

formance could be through the use of hybrid solar cells. Hybrid solar cells consist of both organic and inorganic constituents. As mentioned previously, Coakley and McGehee (2003) identified the ideal morphology for polymer solar cells through the incorporation of an inorganic material into a diblock copolymer morphology. In particular, a conjugated polymer was infiltrated into films of mesoporous titania, which had been created using a structure-directing self-assembling diblock copolymer.

However, it is the application of high aspect ratio nanorods which have drawn the most attention. Their elongated structure facilitate charge transport, while the band gap can be tuned by varying the nanorod radius. This enables the absorption spectrum of the devices to be tailored to overlap with the solar emission spectrum (Huynh, 2002). At present the nanorods in polymer solar cells are typically incorporated into a polymer matrix. An alternative to this approach is to incorporate the nanorods into either a polymer blend or diblock copolymer system (Balazs, 2000; Buxton, 2004). An example of how nanorods can be corralled into the domain of a diblock copolymer is shown in Figure 3. Figure 3 depicts rods which are selectively incorporated into a diblock copolymer morphology, which causes the nanorods to form a percolating structure which spans the system. While these structures have been shown to possess superior mechanical and electrical properties (Buxton, 2004), it is hoped that their photovoltaic properties might also be improved due to the percolation of nanorods. Interestingly, Wang *et al.* (2007) have recently reported a new hybrid solar cells consisting of a polymer and multiarmed CdS nanorods. They found that the solvent used when spin coating these devices can play a crucial role in dispersion. However, it is unclear how the multiarmed structure of the nanoparticles will benefit charge transport in these device. Rather, the orientation of nanorods perpendicular to the film would be expected to increase charge mobility, and hence device performance. To this effect,

nanorods have been grown from the substrate in an attempt to realize an ideal device structure with these hybrid constituents (Snaith, 2005). However, it might be more advantageous to have an internal morphology self-assemble from the constituents to reduce processing costs.

A variation on using nanorods has been to incorporate dye-functionalized carbon nanotubes in to polymer solar cells (Bhattacharyya 2004). The premise of these devices is for the dye to absorb the incident light over a wide range of wavelengths, and for the interaction of dye molecules with both the nanotubes and polymer to facilitate the efficient transfer of electrons to the nanotubes and the holes to the polymer. Furthermore, the dye molecule can be chosen to ensure an absorption spectrum which closely matches the solar spectrum. This opens up the possibility of not only absorbing more sunlight, but also of designing a solar cell with an absorption gradient.

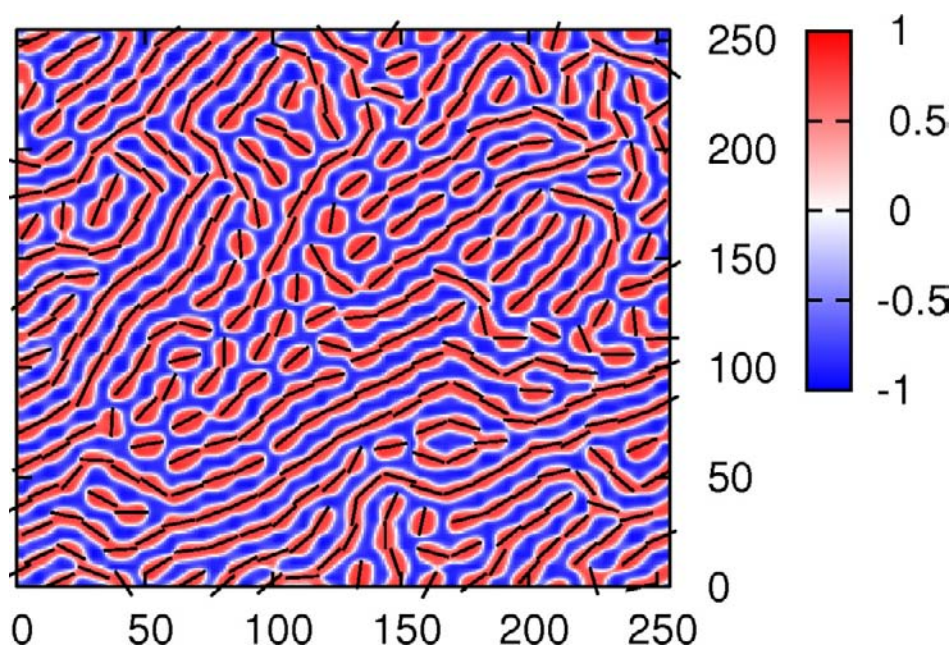
Similar to tandem device, different dyes could be used throughout the solar cell ensuring that large band gap dyes are closer to the top surface and smaller bandgap dyes are closer to the substrate.

The inclusion of nanoparticulates as a constituent in polymer solar cells has drawn further interest with the recent observation that PbSe quantum dots can yield multiple excitons from a single absorbed photon (Schaller, 2004). While, at present, there is no way to extract the photogenerated charge carriers from these quantum dots this observation could open the door to similar phenomena in other nanoparticulates.

COMPUTER SIMULATIONS

Computer simulations are a powerful tool for exploring the device physics of polymer solar cells. In particular, computer models can provide key in-

Figure 3. The effects of corraling nanorods into a single phase of a phase separating polymer blend. Predicted nanorod percolation in a diblock copolymer using computer simulations. The black lines represent the nanorods, while the difference in concentration between the two polymer species is depicted as a contour plot. See Balazs (2001) or Buxton (2004) for computational details.



sights into the internal mechanism of these devices in a way which would be difficult experimentally. For example, while charge recombination can be inferred from experimental data, in computer simulations it is possible to identify the exact location and rate at which charge recombination occurs. However, the outcome of any computer model is only as accurate as the assumptions and insights used to derive the model, and the input parameters used. Furthermore, precise agreement between computer simulations and experimental data is most likely either fortuitous or as a result of fitting parameters. While the quantitative ability of computer simulations to predict polymer solar cell performance is spurious, computer simulations can still provide an invaluable wealth of qualitative insights and predictions. There have been a wide range of computer models developed for analyzing polymer solar cells. The main two models are the drift diffusion model and the Monte Carlo model.

DRIFT-DIFFUSION MODEL

The drift-diffusion model captures the drift of charge carrier concentrations in an electric field and the diffusion of charge carrier concentrations due to gradients in the concentrations (Selberherr, 1984). Typically in an inorganic device, the drift-diffusion model evolves through the self-consistent solution of Poisson's equation and the continuity equations for both electrons and holes. While this model has only recently found application in modeling organic devices, it is a well established and successful technique for modeling inorganic semiconductor devices (Selberherr, 1984). Most of the modeling work on organic devices involves the simulation of organic light emitting diodes (OLED's) (Yang, 2000; Crone, 2000; Blades, 2000; Ruhstaller, 2001; Lee, 2004) whilst, in contrast, there has been less focus on photovoltaic devices. Gregg and Hanna (Gregg, 2003) demonstrated the fundamental differences between inorganic and organic devices by utiliz-

ing a standard one-dimensional drift-diffusion model of an inorganic system, but to mimic how exciton dissociation occurs only at DA interfaces, limited electron and hole generation exclusively to the interface. This demonstrated how charge carriers can be extracted entirely due to internal concentration gradients; charge-carriers can diffuse from regions of high concentration at the DA interface to regions of lower concentration at the electrodes, thus proving an important mechanism of charge extraction. However, this model did not account for exciton generation, diffusion, or dissociation. Barker *et al.* (Barker, 2003) developed a one-dimensional drift-diffusion model specifically for organic devices to capture a bilayer system. Good agreement with experimental data was obtained. They simulated the generation of electrons and holes at the DA interface by considering the fraction of light that was likely to lead to charge separation, but did not model the concentration of excitons directly. Furthermore, in terms of the charge-carrier continuity equations, the acceptor and donor regions were essentially solved separately, with electron concentration in the acceptor domain solved separately from the holes in the donor material. Haerter *et al.* (Haerter, 2005) have simulated a one-dimensional device, and have gone further by allowing the interface to be 'broader' in order to capture the effects of phase separation. They considered electrons and holes to be produced at internal interfacial regions and allowed the charge carriers to move throughout the entire system, taking into consideration the presence of these internal interfaces. However, in this one-dimensional model, morphological effects were taken into consideration by having a simple one-dimensional variation in properties. Recently, Koster *et al.* (Koster, 2005) have developed an equilibrium one-dimensional drift-diffusion model for polymer:fullerene bulk heterojunctions solar cells. However, the device was considered to consist of a single semiconductor material and charge generation was considered to occur uniformly through the device. Even

though current-voltage curves were obtained which matched experimental data very well, the effects of internal morphology and variations in exciton density were not incorporated into their model. More recently, Buxton and Clarke (2006) developed a two-dimensional model of polymer solar cells which takes into consideration exciton generation, diffusion and dissociation (Buxton, 2006; Buxton, 2007). This model has also been used by Shah and Ganesan (2009). As this is the most cutting-edge drift-diffusion model of polymer solar cells it is worth describing in more detail.

The drift-diffusion model involves the solution of continuity equations for electron (n) and hole (p) concentrations, and exciton (x) concentrations. These are updated along with the Poisson's equation for the electrostatic potential (ϕ). These four equations can be written as

$$\nabla \cdot (\epsilon \nabla \psi) = -q(p - n) \quad (1)$$

$$\frac{\partial n}{\partial t} = D(\mathbf{E}, x) - R(n, p) - \frac{1}{q} \nabla [qn\mu_n \nabla \psi - k_\beta T \mu_n \nabla n] \quad (2)$$

$$\frac{\partial p}{\partial t} = D(\mathbf{E}, x) - R(n, p) - \frac{1}{q} \nabla [-qp\mu_p \nabla \psi - k_\beta T \mu_p \nabla p] \quad (3)$$

$$\frac{\partial x}{\partial t} = G(\mathbf{r}) + \frac{1}{4} R(n, p) - R(x) - D(\mathbf{E}, x) - \frac{1}{q} \nabla [-k_\beta T \mu_x \nabla x] \quad (4)$$

where the first equation is Poisson's equation which relates the electrostatic potential to the concentration of charged particles, ϵ is the permittivity and q the elementary charge. The second and third equations are the continuity equations for the electron and hole concentrations, respectively, where μ_i is the mobility of species i , k_β is the Boltzmann constant and T is the temperature. The flux of these charge carriers are dictated by two terms (gradient terms in the second and third equations). The first term involves the gradient

of the electrostatic potential and accounts for the drift of charges in the local electric field. The second term involves gradients in the charge carrier concentrations themselves and accounts for the diffusion of charge carriers from regions of high concentration to regions of low concentration. The charge carriers can be created via the dissociation of excitons and this can be described by Onsager's theory for electrolyte dissociation, given by (Goliber 1984)

$$D(\mathbf{E}, x) = xN_f \int_0^\infty k_D(\mathbf{E}, a) F(a) da \quad (5)$$

where $k_D(\mathbf{E}, a)$ is the electric-field dependent rate constant given by Braun (Braun 1984) and is of the form

$$k_D(\mathbf{E}, a) = K_R \frac{3}{4\pi a^3} e^{-\Delta E/k_\beta T} \left[1 + b + \frac{b^2}{3} + \frac{b^3}{18} + \frac{b^4}{180} + \dots \right] \quad (6)$$

where ΔE is the binding energy, minus the difference in electron affinity, $K_R = q\langle\mu\rangle / \epsilon_0\langle\epsilon_r\rangle$ (where $\langle \dots \rangle$ represents spatially averaged values) and $b = q^3 |\mathbf{E}| / 8\pi\langle\epsilon\rangle k_\beta^2 T^2$. Because of the local disorder in polymeric materials the dissociation rate is integrated over a Gaussian distribution of separation distances, a . $F(a) = a^2 e^{-a^2/a_0^2}$ represents this distribution function (a_0 is a characteristic length of 1nm) and $N_f = 4 / \pi^{1/4} a_0^3$ is a normalization factor (Goliber 1984). The charge-carrier concentrations are reduced through the recombination term, $R(n, p)$. Free charge carriers recombine with a recombination rate of the Langevin form, $R(n, p) = q(\mu_n + \mu_p)pn / \epsilon$. A fraction (commonly taken as $1/4$) recombine to form singlet excitons and, therefore, this term also appears in the fourth equation which describes the continuity equation for excitons. The dissociation term also appears in the fourth equation as exciton dissociation reduces the concentration of excitons. The fourth evolution equation also includes a term

which account for the recombination, or decay, of excitons $R_x = x / \tau_x$, where τ_x is the average lifetime of an exciton. The photogeneration of excitons is given by

$$G(\mathbf{r}) = \sum_i \Phi_i(r_x) \alpha_i \exp^{-\alpha_i(L_y - r_y)} \quad (7)$$

where Φ_i is the incident photon flux, which we take to be uniform across the film (independent of r_x), L_y is the location of the top surface and r_y the distance through the film thickness. The frequency, ν_i , dependent absorption coefficient, $\alpha_i \propto \exp[-(\nu_i - m)^2 / (2\sigma^2)] / \sigma\sqrt{2\pi}$, is assumed to have a Gaussian distribution with an average, $m=500\text{nm}$, a standard deviation, $\sigma = 75\text{nm}$, and a peak value of $\alpha_0 = 2 \times 10^5 \text{cm}^{-1}$.

Current transport in organic semiconductors is a hopping process which can be phenomenologically captured with a field-dependent carrier mobility of the Poole-Frenkel form (Frenkel 1938),

$$\mu = \mu_0 \exp(\gamma\sqrt{|\mathbf{E}|}) \quad (8)$$

The effects of internal heterogeneity and, therefore, internal interfaces, can be included in this model. One can adopt the strategy of Ruhstaller et al. (Ruhstaller 2001) for simulating the hopping process at internal interfaces. They assume that the hopping rate between two sites differing in energy by ΔE to be proportional to $\exp[-(\Delta E + E_p)^2 / 4kTE_p]$, where E_p is the polaron binding energy.

The metal-semiconductor interfaces at the electrodes can be simulated using the boundary conditions of Scott and Malliaras (Scott, 1999). The precise form of the current in these Schottky barriers can be found in either Barker *et al.* (Barker, 2003) or Lalic and Inganas (Lalic, 2005).

Since the variables in the above equations are of different orders of magnitude, and can vary considerably throughout the heterogeneous system, the above equations and variables should be scaled (Selberherr, 1984). The concentrations can be scaled by N , which is chosen such that the spatial discretization is scaled by a Debye length of $\Delta x = \sqrt{\epsilon k_\beta T / (q^2 N)} = 1\text{nm}$. The electrostatic potential is scaled by $k_\beta T / q$ and the mobilities are scaled by $\mu_{max} = 1 \times 10^{-8} \text{m}^2 \text{V}^{-1} \text{s}^{-1}$. The time scale is scaled by $\Delta x^2 q / \mu_{max} k_\beta T$.

Our initial four equations can now be written in a scaled form as

$$\nabla \cdot (\epsilon \nabla \psi) = p - n \quad (9)$$

$$\frac{\partial n}{\partial t} = D(\mathbf{E}, x) - R(n, p) - \nabla \mathbf{J}_n \quad (10)$$

$$\frac{\partial p}{\partial t} = D(\mathbf{E}, x) - R(n, p) - \nabla \mathbf{J}_p \quad (11)$$

$$\frac{\partial x}{\partial t} = G(\mathbf{r}) + \frac{1}{4} R(n, p) - R(x) - D(\mathbf{E}, x) - \nabla \mathbf{J}_x \quad (12)$$

where J_n , J_p , and J_x are the concentrations fluxes for electrons, holes and excitons, respectively. The exciton concentration flux is simply of the form $-\mu_x \nabla_x$.

The Scharfetter-Gummel method (Scharfetter 1969) must be used to obtain the charge-carrier fluxes. For example, the flux for the electron concentration in the x-direction can be shown (via solution of the ordinary differential equation and subsequent finite difference approximation) to be of the form (Scharfetter 1969)

$$J_n(x) = n\mu_n \frac{\partial \psi}{\partial x} - \mu_n \frac{\partial n}{\partial x} = \frac{\mu_n}{\Delta x} [B(\psi_i - \psi_{i+1}) - B(\psi_{i+1} - \psi_i)] \quad (13)$$

where $B(x) = x / (e^x - 1)$ is the Bernoulli function and ψ_i is the electrostatic potential at position i . We can, therefore, write the full discretized equations in the following form:

$$\begin{aligned} & \epsilon_{i+\frac{1}{2},j} \psi_{i+1,j}^{t+1} + \epsilon_{i-\frac{1}{2},j} \psi_{i-1,j}^{t+1} + \epsilon_{i,j+\frac{1}{2}} \psi_{i,j+1}^{t+1} + \epsilon_{i,j-\frac{1}{2}} \psi_{i,j-1}^{t+1} \\ & - (\epsilon_{i+\frac{1}{2},j} + \epsilon_{i-\frac{1}{2},j} + \epsilon_{i,j+\frac{1}{2}} + \epsilon_{i,j-\frac{1}{2}}) \psi_{i,j}^{t+1} = (p_{i,j}^t - n_{i,j}^t) \end{aligned} \quad (14)$$

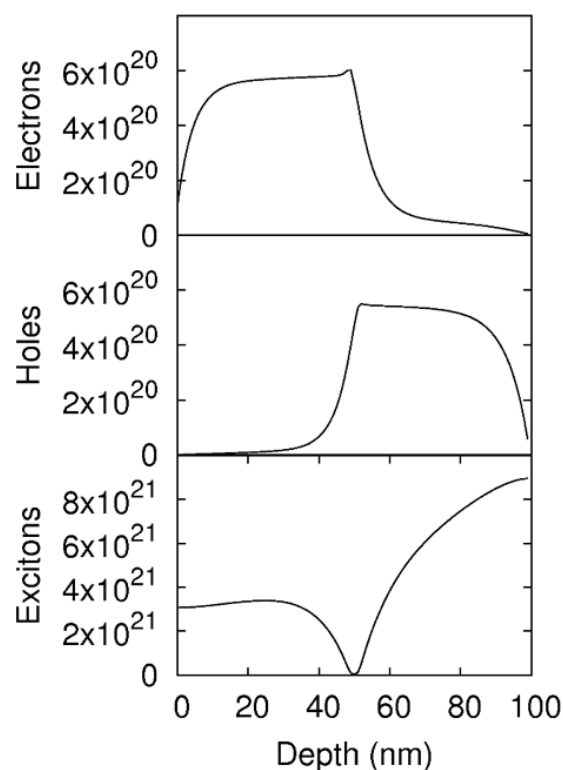
$$\begin{aligned} & \frac{n_{i,j}^{t+1} - n_{i,j}^t}{\Delta t} = D(\mathbf{E}, x_{i,j}^t) - R(n_{i,j}^t, p_{i,j}^t) \\ & + \mu_{i+\frac{1}{2},j}^n B(\psi_{i+1,j}^{t+1} - \psi_{i,j}^{t+1}) n_{i+1,j}^{t+1} \\ & + \mu_{i-\frac{1}{2},j}^n B(\psi_{i-1,j}^{t+1} - \psi_{i,j}^{t+1}) n_{i-1,j}^{t+1} \\ & + \mu_{i,j+\frac{1}{2}}^n B(\psi_{i,j+1}^{t+1} - \psi_{i,j}^{t+1}) n_{i,j+1}^{t+1} \\ & + \mu_{i,j-\frac{1}{2}}^n B(\psi_{i,j-1}^{t+1} - \psi_{i,j}^{t+1}) n_{i,j-1}^{t+1} \\ & - \left[\mu_{i+\frac{1}{2},j}^n B(\psi_{i,j}^{t+1} - \psi_{i+1,j}^{t+1}) + \mu_{i-\frac{1}{2},j}^n B(\psi_{i,j}^{t+1} - \psi_{i-1,j}^{t+1}) \right. \\ & \left. + \mu_{i,j+\frac{1}{2}}^n B(\psi_{i,j}^{t+1} - \psi_{i,j+1}^{t+1}) + \mu_{i,j-\frac{1}{2}}^n B(\psi_{i,j}^{t+1} - \psi_{i,j-1}^{t+1}) \right] n_{i,j}^{t+1} \\ & \frac{p_{i,j}^{t+1} - p_{i,j}^t}{\Delta t} = D(\mathbf{E}, x_{i,j}^t) - R(n_{i,j}^t, p_{i,j}^t) \\ & + \mu_{i+\frac{1}{2},j}^p B(\psi_{i,j}^{t+1} - \psi_{i+1,j}^{t+1}) p_{i+1,j}^{t+1} \\ & + \mu_{i-\frac{1}{2},j}^p B(\psi_{i,j}^{t+1} - \psi_{i-1,j}^{t+1}) p_{i-1,j}^{t+1} \end{aligned} \quad (15)$$

$$\begin{aligned} & + \mu_{i,j+\frac{1}{2}}^p B(\psi_{i,j}^{t+1} - \psi_{i,j+1}^{t+1}) p_{i,j+1}^{t+1} \\ & + \mu_{i,j-\frac{1}{2}}^p B(\psi_{i,j}^{t+1} - \psi_{i,j-1}^{t+1}) p_{i,j-1}^{t+1} \\ & - \left[\mu_{i+\frac{1}{2},j}^p B(\psi_{i+1,j}^{t+1} - \psi_{i,j}^{t+1}) + \mu_{i-\frac{1}{2},j}^p B(\psi_{i-1,j}^{t+1} - \psi_{i,j}^{t+1}) \right. \\ & \left. + \mu_{i,j+\frac{1}{2}}^p B(\psi_{i,j+1}^{t+1} - \psi_{i,j}^{t+1}) + \mu_{i,j-\frac{1}{2}}^p B(\psi_{i,j-1}^{t+1} - \psi_{i,j}^{t+1}) \right] p_{i,j}^{t+1} \\ & \frac{x_{i,j}^{t+1} - x_{i,j}^t}{\Delta t} = G(\mathbf{r}) + \frac{1}{4} R(n_{i,j}^t, p_{i,j}^t) \\ & - R(x_{i,j}^t) - D(\mathbf{E}, x_{i,j}^t) \\ & + \left[\mu_{i+\frac{1}{2},j}^x x_{i+1,j}^{t+1} + \mu_{i-\frac{1}{2},j}^x x_{i-1,j}^{t+1} + \mu_{i,j+\frac{1}{2}}^x x_{i,j+1}^{t+1} + \mu_{i,j-\frac{1}{2}}^x x_{i,j-1}^{t+1} \right. \\ & \left. - \left(\mu_{i+\frac{1}{2},j}^x + \mu_{i-\frac{1}{2},j}^x + \mu_{i,j+\frac{1}{2}}^x + \mu_{i,j-\frac{1}{2}}^x \right) x_{i,j}^{t+1} \right] \end{aligned} \quad (17)$$

where $n_{i,j}^t$ is the concentration of electrons at discrete position i,j and time t . The mobilities are defined off lattice and $\mu_{i+1/2,j}^n$ represents the mobility of electrons at the position $i + 1/2, j$. These discrete equations can now be solved semi-implicitly. In other words, each of the above equations represent a system of linear equations which can be solved separately. All four equations are solved in turn using the conjugate gradient method at each time step. In one dimensions this model is very fast. For example, Figure 4 shows the results for a bilayer device which took less than 2 minutes to run on a single processor. However, simulations of higher dimensions can be more computationally demanding.

The main benefits of the drift-diffusion model is that the input parameters are taken directly from experimental studies. However, the

Figure 4. Electron, hole, and exciton concentrations in a bilayer device. The DA interface is at a depth of 50nm in a 100nm thick film. Note that the electrons and holes are largely confined to their separate domains (although some overlap in concentration, and hence recombination, occurs near the DA interface). See Buxton (2007) for more computational details.



drift-diffusion model can be more computationally expensive than other alternatives, such as the Monte Carlo method, in multiple dimensions and the Monte Carlo method can also directly take into consideration atomistic configurations.

MONTÉ-CARLO MODEL

Dynamical MC models have found general applicability in simulating inorganic systems for many years (Jacoboni, 1989), but have only recently been used to study polymeric systems (scheidler, 1996;

Watkins, 2005; Offermans, 2005; Frost, 2006; Athanasopoulos, 2007; Marsh, 2007). These models progress through successive rate-dependent events in the system, such as charge hopping or exciton dissociation. Individual electrons, holes and excitons are updated on a regular lattice depending upon the rates at which different events are likely to occur. This technique has recently emerged as a promising method for capturing the physics of polymer solar cells. Using a dynamical MC model including exciton diffusion, exciton dissociation, charge recombination, and charge transport Watkins *et al.* (2005) explored the relationship between the scale of random phase separation and the efficiency of the solar cells. They found a strong dependence on interfacial area (required for exciton dissociation) and also concluded that charge mobility is an important determinant of peak efficiency. Furthermore, they found that an ordered morphology can significantly enhance the device efficiency over disordered morphologies. Frost *et al.* used MC models to both generate homopolymer chain structures (using a slithering snake algorithm) and to simulate charge transport (Frost, 2006). Interestingly, they separated intra-chain and interchain hopping rates and, as such, their model can be used to investigate the effects of chain orientation on charge carrier mobility.

In a dynamical MC model of photovoltaic performance the excitons, electrons and holes are simulated discretely on a regular lattice (where single site occupancy is imposed) (Scheidler, 1996). This microscopic approach must be dynamically correct and a proper temporal sequence of events maintained. The simulation evolves through the identification of rates for various events (Scheidler, 1996). In particular, an exciton can hop from its current site i to a neighboring site j with a rate

$$w_{ij} = w_e \left(\frac{R_0}{R_{ij}} \right)^6 f(E_i, E_j) \quad (18)$$

where R_{ij} is the distance between sites i and j , R_0 is the exciton localization radius, and w_e is the rate at which hopping is attempted (Watkins 2005). The function $f(E_i, E_j)$ can be given by

$$f(E_i, E_j) = \begin{cases} \exp\left(-\frac{E_j - E_i}{kT}\right) & E_j > E_i \\ 1 & E_j < E_i \end{cases} \quad (19)$$

E_i and E_j being the energies of occupation of sites i and j , respectively. An exciton may also recombine at a rate of w_{cr} , or dissociate at a DA interface with a rate of w_{diss} (Watkins, 2005). Charge carriers may also hop with a rate, in the case of an electron, of

$$w_{ij} = w_n \exp(-2\gamma R_{ij}) f(E_i, E_j) \quad (20)$$

where w_n is the rate at which hopping is attempted for an electron. γ is a localization constant which can be related to the charge mobility. Oppositely charged particles on adjacent sites may recombine at a rate of w_{cr} . The charge can also leave the system if the charge is next to the appropriate electrode, at a rate of w_{ce} (Watkins, 2005).

The dynamical MC method is typically evolved in time using the first reaction method (FRM). For each rate in the system a corresponding waiting time is calculate from

$$\tau = -\frac{1}{w} \ln(\epsilon[0 : 1]) \quad (21)$$

where $\epsilon[0 : 1]$ is a random number uniformly distributed between 0 and 1 (Scheidler, 1996). The event with the smallest τ for a given particle is then chosen as the event for that particle which is added to a list of events.

Only one event for each particle is added to the list. The events list contains these events, stored in order of increasing τ . At each time step the event at the start of the list, with the smallest τ , is executed and removed from the list. An amount of time τ is assumed to have passed during the execution of this event and all other events in the list have their waiting time reduced by this value. All new events are slotted into the list according to their waiting times, maintaining the correct temporal sequence. This algorithm is continually evolved until steady state is obtained. In particular, when there is a balance between charges being created from the exciton dissociation events and charge being removed from the system (either recombining with other charge or being extracted via the electrodes) then the system is considered to be in a steady state.

This method provides a simple and intuitive way to capture the photovoltaics of polymer solar cells in three-dimensions. Furthermore, updating individual excitons, electrons and holes in this microscopic approach enables the diblock copolymer chain structure (in particular, chain orientation) to be taken into account in a relatively straight forward manner. In other words, the interchain and intrachain hopping rates can be assigned to ensure charge carrier mobility is greatest along the polymer backbone and significantly reduced if due to a hopping process (Frost, 2006). The only drawback of this model is that the input parameters are not easily identifiable from experimental studies.

STRUCTURE-PROPERTY RELATIONS

One of the most important advantages of using computer simulations is the ability to first simulate the morphology of these devices, before feeding these morphologies directly into a computer model

of photovoltaic performance. The input to these photovoltaic models is likely to be the local concentrations of donor and acceptor materials, and possibly the local orientation of polymer chains. There are many models of polymer morphology which could be used including continuum models and atomistic models, and it is worth briefly mentioning them here.

Continuum or coarse-grained models include the Cahn-Hilliard model, the self-consistent field theory and the lattice Boltzmann model. The Cahn-Hilliard model is often used in conjunction with the Flory-Huggins theory which describes the entropy of mixing different polymer species (Cahn, 1958; Buxton, 2005). This model has also been extended to include the effects of nanoparticles and nanorods (Balazs, 2001). The self-consistent field theory incorporates the microscopic effects of polymer chains, and yields more accurate morphologies than the Cahn-Hilliard model at the expense of computational efficiency (Thompson, 2001). The lattice Boltzmann model is traditionally a model of hydrodynamic flows, but has also been extended to capture polymer systems (Succi, 2001). Continuum models will yield the local concentrations of donor and acceptor phases during phase separation, but generally lack individual atomistic details. In order to capture the effects of individual polymer chains it is necessary to use atomistic methods such as a Monte Carlo model or a Molecular Dynamics model. The Monte Carlo model is in general an equilibrium model which samples possible polymer chain locations and conformations and selects configurations which are more energetically favorable. In contrast, the Molecular Dynamics model integrates the Newtonian laws of motion for individual atoms and updates their positions in time. However, it is often difficult to reach an equilibrium structure using a dynamic model as the time scales are computationally prohibitive. The atomistic models yield both the domain structure of phase separating polymer systems, and the local orientation of polymer chains, but

are significantly more computationally expensive than continuum models.

The integration of a morphological model and a photovoltaic model enables the morphological effects to be considered directly and the full history (from constituents and processing to performance) to be captured. While this improves the predictive capabilities of these computer simulations, it is the insights that can be gained about the internal device physics of organic solar cells which can be most fruitful. For example, through simulating the photovoltaics of actual morphologies it is possible to observe how exciton concentrations vary near DA interfaces, or how the build up of electrons and holes in morphological cul-de-sacs results in charge recombination (Buxton, 2006). It is, therefore, an important consideration if computer simulations are to be more accurate, reveal experimentally observable trends and lead experiments in device design.

An interesting development in Monte Carlo simulations involves the ability to take the output from an atomistic model and incorporate this atomistic structure into the Monte Carlo model through site hopping probabilities. While this has only been realized in simple systems using a slithering snake algorithm for the morphology (although the conjugated nature of these polymers, and large persistence lengths, make the slithering snake model unsuitable) it could be extended to more complicated models (Frost, 2006). For example, an off-lattice model could be used to determine the morphology, and the chain positions could be used to determine an irregular network for the Monte Carlo photovoltaic model. It is also possible to introduce anisotropic mobilities in the drift-diffusion model and incorporate similar chain orientation effects, in a more coarse-grained manner. While the drift-diffusion model cannot account for the orientation of individual chains it can take the average orientation for a given location and consider the charge and exciton mobility to be greater along the chain direction (Shah, 2009). For example, Shah and Ganesan recently

fed the output from a self-consistent field theory model of rod-coil block copolymers, including information regarding the morphology and average chain orientation, into a drift-diffusion model (Shah, 2010).

FUTURE RESEARCH DIRECTIONS

Future work in polymer solar cells will likely concentrate on developing new polymer materials which absorb light over more of the solar spectrum and have higher mobilities. Semi-crystalline polymer materials will also attract further attention as they offer the possibility of significantly increasing charge mobility between adjacent chains. In particular, diblock copolymer systems will continue to be developed with crystalline ordering within the polymer domains. This offers the promise of small domain sizes and high mobility, which would significantly improve device performance.

The use of polymers for photovoltaics opens up the possibilities of developing flexible devices at relatively low cost. Furthermore, the ability of these polymer materials to self-assemble into complex, and hopefully beneficial, structures opens up the possibility of a simple one-step processing. It may even be possible to develop polymer solar cells which could be painted, or sprayed, onto a surface. Polymer solar cells will likely compete with other energy-generating technologies as a consequence of their low-costs and ease of fabrication. The portability and flexibility of polymer solar cells will hopefully see their increased use, especially in third-world countries.

Inorganic nanorods are the perfect additive for polymer solar cells. The nanorods can provide a one-dimensional pathway along which charges can be transported, while the thickness of the nanorods control the absorption spectra (Huynh, 2002). In particular, if these nanorods can be arranged in such a way that they percolate and allow charge transport throughout the device then these hybrid systems might offer a route to

creating low-cost and efficient flexible solar cells. Further research is also needed to determine how to extract multiple charges from the absorption of a single photon. While this phenomena has been observed in isolated quantum dots it has yet to be achieved in photovoltaic cells.

CONCLUSION

The detrimental effects of global warming and rising energy costs will continue to drive our future need for low-cost clean energy technologies. Polymer solar cells could provide, at least a small part of, our solution to these environmental problems. Furthermore, polymer solar cells will open up new avenues for the application of photovoltaic technologies by enabling the construction of flexible and more portable devices. However, before polymer solar cells can be considered economically viable there must be a significant increase in power conversion efficiencies. Future research in these devices, therefore, will attempt to increase their performance. With many avenues of research being pursued these photovoltaic systems will increasingly offer a promising alternative to current polluting fossil fuel technologies.

A brief introduction to polymer solar cells has been presented, which concentrated on both the device physics and the internal mechanisms of energy conversion. The key component of polymer solar cells is the DA interfaces, which play the pivotal role of dissociating excitons and generating free charge. The limited diffusion of excitons necessitates domain sizes on the 10nm scale to ensure that most excitons reach a DA interface prior to geminate recombination. In particular, the role of nanotechnology in creating thin films with thicknesses on the order of 100nm, with features on the 10nm scale, have been reviewed. In particular the possibility of using diblock copolymers and nanorods to create the desired internal morphologies of these films, which play a crucial role in determining the photovoltaic performance

of the devices, has been discussed. An idealized morphology consisting of interdigitized domains has been identified which would maximize both exciton dissociation and charge extraction. The role of chain orientation inside the domains, however, has only recently been studied and the possibility of exploiting anisotropic mobilities, for improved photovoltaic performance, has yet to be investigated.

The computational tools used to investigate the physics of polymer solar cells have also been presented. In particular, the drift-diffusion and Monte Carlo models of photovoltaic performance have been described. These techniques offer us the opportunity to not only reproduce experimental results but to also reveal insights into the internal mechanisms of these devices (in ways that would be unattainable to experimental studies) and provide alternative designs which could guide future experimental investigations. The role of computer models to identify structure-property relations, and identify the ideal structures necessary for device performance, will be crucial to the further development of this technology. In addition, computer simulations can also investigate the constituents and processing history required to create these ideal structures, and ultimately model the entire history of a polymer solar cell.

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KEY TERMS AND DEFINITIONS

Donor-Acceptor (DA) Interface: The interface between two materials where one material (the donor) has a low ionization potential and the other (the acceptor) has a high electron affinity. Such interfaces are required to dissociate an exciton.

Drift-Diffusion: A continuum model which can easily be experimentally parameterized and has been successfully used to model solar cells since the 1950's.

Exciton Dissociation: The separation of a coulombically bound electron and hole to create a free electron and hole which are no longer bound together.

Exciton: A mobile excited state consisting of a coulombically bound electron and hole.

Hopping: The inefficient transport of free charge carriers between neighboring polymer chains.

Hybrid Solar Cells/Devices: Solar cells which are constructed from a mixture of organic and inorganic constituents.

Monte Carlo (MC): An atomistic model that can capture the physics of solar cells.

Nanotechnology: The manipulation of structures in material science on length scales smaller than 100nm.

Polymer Solar Cell: A photovoltaic device which is constructed from organic polymer constituents.

Recombination: The combination either coulombically bound electrons and holes (excitons), or free electrons and holes, to lose charge carriers from the device.

Chapter 10

Low-Cost III-V Compound Semiconductor Solar Cells: Progress and Prospects

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ABSTRACT

The prospects for cost-effective flat plate (non-concentrator) solar cells based on III-V compound semiconductors (e.g., GaAs, InP, AlAs, and their alloys) are reviewed. Solar cells made in III-V materials are expensive, but outperform solar cells in every other materials system. The relatively high cost of compound semiconductor wafers necessitates a means to eliminate their use as substrates for epitaxial growth of conventional III-V solar cells. There are several approaches to this end, including thin-film solar cells on low-cost, dissimilar substrates such as glass, ceramics, and metal sheets; III-V solar cells epitaxially grown on silicon wafers; film transfer ('epitaxial lift off') techniques that allow re-use of the seeding substrate; and assembled arrays of small III-V solar cells on low-cost substrates. Grain boundary effects in polycrystalline III-V films can severely degrade solar cell performance, and impede the application of established thin-film technologies, as developed for amorphous silicon and II-VI semiconductor photovoltaics, to III-V semiconductor-based solar cells. The nearly fifty years of effort in developing thin-film III-V solar cells has underscored the difficulty of achieving large-grain sizes and/or low recombination grain boundaries in polycrystalline films of III-V semiconductors.

INTRODUCTION

One of the more promising thin-film approaches utilizes the epitaxial growth of an (Al)GaAs solar cell on a recrystallized germanium seeding layer deposited on a thermal-expansion matched (inexpensive) substrate such as alumina ceramic.

Recent developments related to 'assembled' arrays of millimeter-sized III-V solar cells made by inkjet and contact printing, parallel transfer, robotic pick and place, and fluidic self-assembly, are in early stages but offer several avenues for high-efficiency III-V solar cells with much reduced costs. These designs often use integrated optics

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to improve light coupling to the array solar cells, and employ a low-cost, flexible polymer substrate.

In this review, we survey the prospects for cost-effective III-V compound semiconductor solar cells for terrestrial power generation. The III-V semiconductors include the binary compounds GaAs, InP, GaN, AlAs, AlP, and InAs, as well as ternary and quaternary alloys between these binaries, e.g., AlGaAs, InGaAs, InGaN, and AlGaAsSb. Currently, high-efficiency III-V solar cells are used as standard equipment for powering satellites and other space vehicles. High-efficiency III-V compound solar cells may also prove essential for economically-viable terrestrial concentrator photovoltaic systems. Our primary focus here, however, is on solar cells for lower-cost, non-concentrator systems—so called *flat plate* arrays with minimal tracking and external optics. In other words, III-V solar cells that might compete directly with silicon solar cells on cost and performance in, for example, stand-alone or grid-connected roof-top solar electric systems. By *non-concentrator*, we are excluding systems with external optics and/or tracking, but not flat-plate systems that use integral optics, such as lensed cover plates or gratings to effect focusing and concentration within the solar cell module.

BACKGROUND

The main attraction of III-V solar cells is their superior performance. III-V solar cells in the form of sophisticated epitaxial multi-junction device structures have demonstrated the highest conversion efficiencies (~40%) of any photovoltaic technology to date. The relevant performance data of various III-V solar cell technologies are summarized in Table 1, along with silicon solar cells that provide a performance benchmark. Secondary advantages of III-V solar cells relative to silicon solar cells include higher radiation resistance (crucial for space power, but not an over-riding consideration for terrestrial photo-

voltaics); more tolerance of increased operating temperatures, and higher operating voltages which reduce series resistance losses. It should be kept in mind that the best commercial silicon solar cells are already at ~20% efficiency (e.g., Sanyo HIT crystalline/amorphous silicon solar cell (Taguchi *et al.* 2005), and therefore, the areal cost of alternative single-junction III-V solar cells with similar efficiencies—and without the leveraging effect of optical concentration—will have to be comparable to that of the current premium single-crystal silicon solar cell technology. By the same reckoning, it can be inferred as a corollary that III-V solar cells that cost more than silicon on an areal basis will need to have a substantially higher conversion efficiency than the best silicon solar cells in order to challenge the predominance of silicon photovoltaics.

Given the intrinsically higher materials and processing costs of conventional III-V solar cells, one might reasonably ask whether such a cost goal is even possible, let alone worth the effort. Ultimately, a low-cost format for III-V solar cells is of interest because it could serve as a basis for subsequent adaptations to very high-efficiency multijunction solar cells. The III-V semiconductor alloys provide ‘tunable’ bandgaps, carrier confinement, various hot carrier effects, and efficient luminescence (for photon recycling), as well as thermophotovoltaic or thermionic operating modes that can be exploited in innovative solar cell designs commonly termed “Third Generation” photovoltaics, with predicted efficiencies in the 30–60% range (Green 2002; Coniber 2007]. Many of these effects and design options are not readily available, nor as well developed with silicon-based devices nor other semiconductors. Such high efficiencies would dramatically reduce balance-of-systems costs for solar electric installations, and also permit use where deployment is limited by available area such as urban rooftops. Novel solar cell design configurations may be enabled by alternative fabrication techniques developed for low-cost III-V solar cells, or alter-

Table 1. Selected solar cell and module efficiencies

	Cell Type	Area (cm ²)	Illumination	Efficiency (%)
multijunction Cells	GaInP/GaAs/Ge	4.0	AM1.5 (1X)	32.0
	GaInP/GaAs	4.0	AM1.5 (1X)	30.3
single-junction Cells	monocrystalline silicon	4.0	AM1.5 (1X)	25.0
	multicrystalline silicon	1.0	AM1.5 (1X)	20.4
	monocrystalline GaAs	1.0	AM1.5 (1X)	26.1
	multicrystalline GaAs on poly Ge	4.0	AM1.5 (1X)	18.4
	monocrystalline InP	4.0	AM1.5 (1X)	22.1
	multicrystalline CIGS	1.0	AM1.5 (1X)	19.4

From M.A. Green *et al.*, 2010.

natively, new high-efficiency III-V solar cell designs may be more compatible with alternative low-cost fabrication methods than with the conventional single-crystal wafer-based epitaxial III-V solar cells as currently used for space power applications. For example, formation of III-V solar cells on insulating substrates can facilitate series interconnection schemes for high-voltage monolithic solar cell arrays. Also noteworthy is the considerable technology developed for solid-state lighting based on III-V semiconductor LEDs that can be exploited for solar cell applications, particular in areas related to packaging and optical coupling. The synergy between LEDs and photovoltaics has discussed and elaborated in several publications (Kurtz 2003;Algora *et al.* 2006).

The high-cost of conventional III-V solar cells is due in large part to the expensive single-crystal (*monocrystalline*) wafers employed as substrates to seed and support epitaxial growth of the solar cell device. Eliminating the need for such substrates would go a long way in reducing the cost of III-V solar cells. Thus, a basic underlying motivation of much of the work reviewed here relates to means for avoiding the high costs associated with epitaxial growth of III-V semiconductors on expensive single-crystal wafers. With respect

to device operation and efficiency, the elimination of the substrate is not disadvantageous due to the strong optical absorption coefficient over the solar spectrum of most of the III-V semiconductors. Accordingly, only very thin ($\sim 2 \mu\text{m}$ or less) films of the semiconductors, supported on a passive substrate, are needed for such thin-film solar cells to reach their performance potential. This concept has long been appreciated and is, of course, the basis for thin-film solar cells such as those based on CdTe, CuInSe₂, amorphous silicon, and other more ‘exotic’ (i.e., non-silicon or III-V) semiconductors.

Thin-film deposition of semiconductors on dissimilar substrates such as glass, metal sheets, or ceramic invariably results in polycrystalline semiconductor material. The performance of electronic and optoelectronic devices made in polycrystalline material is generally inferior to that of the same type of devices made in single-crystal material. Interestingly, while this appears to be true for silicon, germanium, and most III-V semiconductors, it may not be the case for solar cells made from II-VI semiconductors. Visoly-Fisher *et al.* (2004) surmise polycrystalline CdTe/CdS solar cells are more efficient than monocrystalline cells of the same material and design because the grain boundaries do not increase minority

carrier recombination and actually contribute to photovoltaic energy conversion by enhancing the collection of photogenerated carriers. In the particular case reported, the enhancement effect is achieved by post-growth annealing and doping with chlorine that leads to band bending and carrier-type inversion at the grain boundaries. Grain boundaries may also act as sinks to getter certain lifetime-reducing impurities and defects from intragrain regions. With regard to III-V semiconductors, the wide-bandgap nitrides (e.g., GaN) appear to tolerate defects much better than the lower-bandgap III-V's such as GaAs. In the widebandgap III-V nitrides, it has been postulated that grain boundaries confine carriers for more efficient radiative recombination, leading to brighter electroluminescent devices. Although radiative recombination is generally not beneficial for solar cell efficiency (unless photon recycling effects are exploited), this shows another instance where a materials-sensitive aspect of device performance can actually be improved by defects. These observations further suggest that III-V nitride solar cells may better tolerate degraded material quality than do GaAs- and InP-based devices. Similar defect-mediating phenomena have not been observed in III-V materials besides the nitrides. In the past, it has been proposed that selective diffusion down grain boundaries in polycrystalline silicon can create vertical junctions that improve solar cell collection efficiency, and thus enhance short-circuit current (Chu *et al.*, 1980). This benefit is probably more than offset, however, by higher leakage currents and shunting associated with such diffused structures. For GaAs- and InP-based solar cells employing conventional designs and post-growth materials processing, multicrystallinity imposes a substantial performance penalty with these semiconductors, at least for the grain sizes and grain boundary characteristics achieved with commonly-employed thin-film deposition methods. Multicrystalline materials also impede fine-line patterning methods for low-loss grid metallization contacts, and complicate surface tex-

turing processes used to reduce external reflection and induce performance-enhancing light trapping effects that rely on anisotropic etching. In brief, the thin film designs and processes successfully developed for II-VI and amorphous silicon solar cells have not met with success when directly applied to III-V solar cells. The performance of solar cells made in as-deposited films of III-V on inexpensive substrates is considerably less than their single-crystal counterparts. Either novel device designs and materials processing methods that avoid or mitigate the effects of grain boundaries in thin-film III-V solar cells must be realized, or else new device concepts that better utilize relatively expensive materials and processing effort, as discussed in more detail later, must be implemented.

In a first pass on surveying the routes, progress, and prospects of making cheaper III-V solar cells with performance potential of III-V space solar cells, approaches to this end might be categorized as follows: 1. methods of drastically cutting costs in the way conventional III-V solar cells are made, 2. applying monocrystalline/multicrystalline silicon solar cell technology to III-V solar cells, 3. adapting thin-film polycrystalline solar cell technology as used for amorphous silicon, CdTe, and CuInSe₂ to III-V solar cells, or 4. developing completely new technologies that exploit the properties of III-V semiconductors that enable or facilitate novel designs and fabrication processes.

Some of these approaches can be immediately dismissed as lacking much potential. In category 1, the costs of conventional III-V solar cells are dominated by high substrate costs, high epitaxy costs, and high fabrication costs. For various reasons, there appears to be little hope for making III-V wafers sufficiently cheap enough to gain cost parity with silicon wafers. III-V wafers are expensive compared to silicon wafers because gallium and indium are relatively scarce metals. In fact, the scarcity of gallium (and indium) could well prove an insurmountable barrier for III-V solar cells even if made in thin film form. Moreover,

III-V bulk crystals are more difficult to produce than silicon material because the high volatility of the Group V element at the binary melting point requires atmospheres with overpressures of the Group V element and/or encapsulation of the III-V material with molten oxides. Also, the lower thermal conductivity of III-Vs (relative to silicon) and their lower critical resolved shear stress means the conditions for low-dislocation growth of III-V crystals will translate to smaller bulk crystals grown at slower speeds compared to silicon (Jordan *et al.* 1981). For these reasons, III-V semiconductor wafers will most likely cost at least a factor of five or ten more than silicon.

Almost all III-V solar cells are made using metal organic chemical vapor deposition (MOCVD) for growth of the epitaxial solar cell structure. There are probably no fundamental hurdles precluding high-throughput epitaxy, and significant reductions in epitaxy cost per cell appears feasible. With some effort and modification, the screen printing metallization processes, surface texturing, and anti-reflection coating processes developed for high-efficiency silicon solar cells can most likely be developed for III-V solar cells as well. To summarize, although significant cost reductions might well be realized for epitaxy and device fabrication (metallization, anti-reflection coatings), conventional III-V solar cells will remain expensive due to high single-crystal wafer substrate costs.

With regard to category 2, the wholesale adaptation of conventional wafer-based silicon solar manufacturing to III-V solar cells would not yield much cost reduction even if feasible. Silicon solar cells are bulk devices in that there is a substantial contribution to output from light absorption and collection of photo-generated carriers that occurs deep (~ 100 microns) below the surface of incident light. Silicon solar cells require adequate minority carrier lifetimes through the bulk of the entire wafer, and low minority carrier recombination losses at the back surface of the wafer. In contrast, the substrate is not photovoltaically

active in III-V solar cells, and the best approach is to achieve high material quality with respect to minority carrier lifetime in a thin frontal region, as for example, by epitaxial growth, without any reliance on substrate lifetime. Single-crystal or polycrystalline III-V wafers with relaxed material quality requirements and therefore somewhat lower cost can be contemplated as substrates for epitaxial growth. However, casting, directional solidification, sheet formation, dendritic-web growth, and other alternative wafer, sheet or ribbon technologies as employed for silicon solar cells would encounter many of the same limitations cited above for single-crystal bulk crystal growth of III-V ingots. While there is considerable divergence of technology and design criteria between silicon and III-V solar cells with regard to wafer/substrate, epitaxial growth, and device design, some of the high-volume production methods used for silicon solar cells and modules should be transferable to III-V solar cells.

In spite of the general inapplicability of conventional silicon solar cell technology, there is one particular recent development in silicon solar cells worth mentioning for potential application to III-V solar cells: the so-called Sliver[®] silicon solar cell technology developed at Australian National University. Sliver[®] technology (see Figure 1) could offer a means for substantial reductions in materials consumption and cost when applied to III-V wafer-based solar cells. Sliver[®] cells are micromachined as slats from a silicon wafer (as shown in Figure 1a) and then embedded in a transparent light-trapping media (as shown in Figure 1b). In the case of silicon solar cells, this approach decreases silicon usage by a factor of 12. Applied to III-V solar cells, an analogous Sliver[®] process could incorporate a wrap-around epitaxial growth step in place of the diffusion process used to make the p - n junction in silicon solar cells. Also, precious gallium could be recovered from the kerf. While to our knowledge there are no reports of adaptation of Sliver[®] or similar methods to solar cells other than those made with monocrystal-

line silicon, this example illustrates a possible unconventional route to low-cost III-V solar cells.

Category 3 refers to the utilization and adaptation of thin-film solar cell technology commonly employed for II-VI materials and amorphous silicon to III-V solar cells. This approach has comprised the main efforts in developing low-cost III-V solar cells since the mid-1960s and up until recently. The substantial work in this area did not lead to any sustained commercialization efforts and, in fact, indicated there were formidable technical barriers to low-cost, thin-film polycrystalline III-V solar cells. In the late 1990s, the demonstration of a 20% efficiency GaAs solar cell on a polycrystalline germanium substrate addressed some of the technical objections, showing in principle that high-efficiencies could be achieved in large-grain ($\sim$ mm) polycrystalline GaAs films. Further, parallel developments in other thin-film solar cells have generated a highly-developed technology base and infrastructure for thin-film solar cell analysis and production,

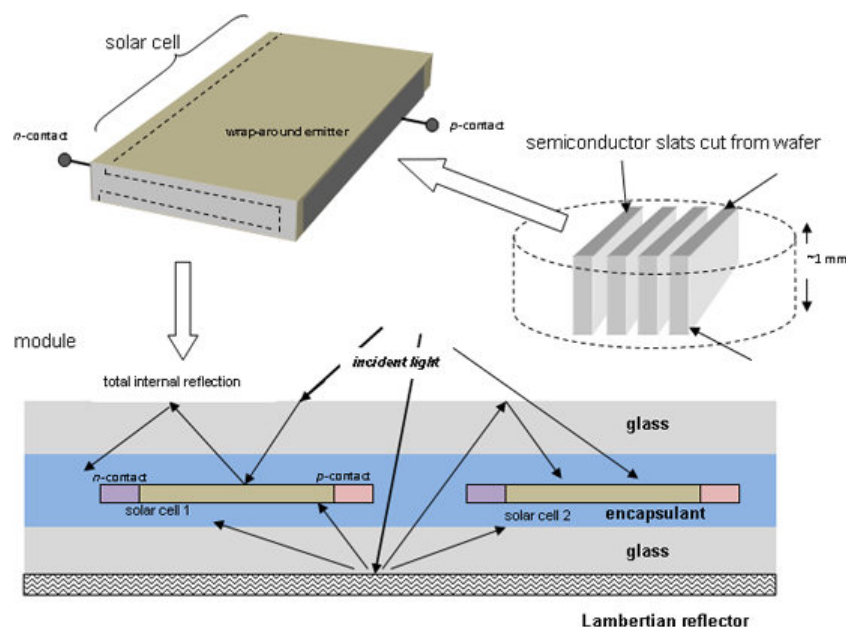
much of which can be applied to III-V thin-film solar cells.

Category 4 includes novel methods developed explicitly for III-V semiconductor optoelectronics, such as heteroepitaxy on silicon, film transfer techniques, microscale printing, fluidic assembly, and nanostructuring of III-V materials. These present some of the more recent and promising avenues for low-cost III-V solar cells, and will be discussed at some length in this review.

PERSPECTIVE

Currently, silicon-based solar cells are the mainstay of the photovoltaics industry. About 90% of solar cells are made from single-crystal (monocrystalline) or polycrystal (multicrystalline) silicon wafers or silicon sheets/ribbons. The dominant position of silicon stems from the good conversion efficiencies of silicon solar cells (15% in commercial modules), the highly-developed

Figure 1. From Weber et al. (2005) showing Sliver[®] silicon cells and embedding in transparent matrix for light trapping and optical enhancement due to embedding the solar cell in a transparent light-trapping media.



silicon technology base (silicon is basis of almost the entire microelectronics industry), the excellent stability of silicon solar cell modules (silicon solar cell modules have thirty-year warranties), and the abundance of silicon (silicon is the second most plentiful element in the earth's crust). Silicon is also non-toxic, in contrast to constituents of some other solar cell technologies. Over the last forty years, many alternative materials technologies have been posed to challenge the prevalence of silicon solar cells, including thin-film solar cells based on cadmium sulfide ($\text{CdS/Cu}_x\text{S}$ heterojunctions), amorphous silicon and related alloys, CdTe , and CuInSe_2 , to name the most prominent materials, and more recently, solar cells based on nanomaterials and organics. Yet silicon solar cell technologies continue to withstand these challenges, and there is more room for further cost reductions and performance improvements in silicon solar cells to help sustain its premier position as the dominant solar cell material.

In contrast, space solar cell technology, that is, photovoltaic devices that provide electric power to orbiting satellites and other space vehicles is currently dominated by GaAs-based solar cells. For satellites and space vehicles, the superior performance and radiation hardness of III-V-based solar cells rationalize their higher costs. Although GaAs-based cells are generally considered too expensive for earthbound solar systems, there is a substantial technology base that can be exploited for producing lower cost versions of these solar cells. This is because, unlike most compound semiconductors employed in various types of thin-film solar cells, GaAs and other III-V semiconductors are widely utilized in optoelectronics (lasers, LEDs, photodetectors) and high-speed electronic devices, and thus there is a considerable science, technology, and infrastructure available for GaAs-based semiconductor devices. Moreover, fundamental understanding of the physics and materials science of III-V semiconductors is considerably greater than materials such as CdTe , CuInSe_2 , and amorphous silicon. However, in

polycrystalline form, the II-VI semiconductors are more developed than polycrystalline III-Vs, since most of the research effort in these materials has focused on polycrystalline thin films, primarily for application to solar cells.

THIN FILM POLYCRYSTALLINE III-V SOLAR CELLS

Early Work, 1960-1980

In this section, we review work on solar cells comprised of thin films of III-V semiconductor formed directly on low-cost, dissimilar substrate materials such as metal sheets or glass. This approach is motivated by related thin-film solar cell technologies developed for CdS , CuInSe_2 , and amorphous silicon photovoltaics.

Vohl *et al.* (1967) reported methods for making thin-film polycrystalline GaAs solar cells on molybdenum and aluminum substrates. The GaAs films were deposited by a close-spaced vapor transport (CSV) process using water vapor as the transport agent (Robinson 1963, Thurmond and Frosch 1964), optimally in a temperature range of 750 to 850 °C. GaAs films formed by such chemical vapor deposition were found superior to those made by sputtering or flash evaporation. The importance of a substrate with a thermal-expansion coefficient closely matched to GaAs was appreciated in order to assure good adhesion of the GaAs film and reduce thermal stress-induced fracture. Aluminum substrates were also feasible but they had limited deposition temperatures due to their low melting point (660 °C). Diffused junction and epitaxial junction devices had poor characteristics attributed to rapid Zn diffusion along grain boundaries. Junctions formed by Pt films and $\text{Cu}_{1.8}\text{Se}$ gave better results, leading to solar cells with efficiencies of 3% (4 cm² area), 4.5% (2 cm² area) and 5% (0.2 cm² area). This work identified many of the key issues in thin-film GaAs solar cells and set the stage as the starting

point for much of the subsequent effort in this area. An early study of evaporated GaAs films (Takahashi 1972) indicated that GaAs material made by simple deposition processes such as evaporation were plagued by defect trapping and other anomalous phenomena. Pulfrey and Russel (1976) used a CSVT process to deposit polycrystalline GaAs films on Mo foil from which Schottky barrier diodes were made. An optimum growth temperature of 725 °C produced GaAs films at a deposition rate of 25 µm/hour. The grains were columnar with lateral dimensions ranging from 10 to 100 microns, and with a bed of stunted grains near the Mo-GaAs interface.

Chu *et al.* (1979) described polycrystalline GaAs films deposited on graphite substrates using a chloride vapor-phase transport process. GaAs films 10-20 microns in thickness exhibited grain sizes comparable to the film thickness. Metal Oxide Semiconductor (MOS) type solar cells made on this material showed efficiencies higher than 6%. The MOS type cell avoids the grain boundary shunting problem associated with junction formation by Zn diffusion. Chu *et al.* (1978) subsequently reported $p^+/n/n$ homojunction GaAs solar cells in polycrystalline GaAs films deposited on tungsten-coated graphite with efficiencies of 8.2% (1 cm² area). The poly GaAs films were approximately 10 microns thick with grain sizes of 2 to 10 microns.

Bachmann *et al.* (1977) developed polycrystalline CdS/InP heterojunction solar cells on graphite substrates with a heavily Zn-doped intermediate layer of GaAs to facilitate ohmic contact between the InP film and substrate. The grain size dimensions of the polycrystalline InP layer were 2-3 microns, and efficiencies of 5.7% were demonstrated.

Johnston (1979) surveyed the early results on polycrystalline III-V solar cells which are summarized in Table 2, and surmised that the prospects for III-V thin film solar cells for terrestrial power generation at this juncture were somewhat uncertain. As-deposited III-V semiconductor films on

foreign substrates typically exhibited grain sizes less than 10 microns. Later work has generally not yielded any dramatic improvements in as-deposited grain size.

For GaAs films deposited directly on dissimilar substrates, deleterious electrical effects associated with grain boundaries significantly limited solar cell performance, and surmounting the 10% efficiency ‘barrier’ was far from certain. Modeling indicated the sensitivity of solar cell performance to grain boundary dimensions, but the modeling results (discussed below) were highly-dependent on many assumptions regarding the crystallographic nature and chemical composition of grain boundaries. This resulted in two lines of research: 1) increasing grain size of as-deposited III-V films, and 2) methods of electrical passivating grain boundaries to mitigate their effects on solar cell performance. A third line of research, post-growth enhancement of grain size, such as by recrystallization/annealing, has also been pursued but with limited success, as III-V materials are difficult to recrystallize. The most promising route for GaAs thin film solar cells appears to be the use of a recrystallized Ge interlayer on the low-cost substrate. Ge is relatively easy to recrystallize and achieve large grain sizes, and such Ge layers can seed the epitaxial growth of large-grain GaAs, as the GaAs overlayer will replicated the grain structure of the Ge layer. Efforts along these lines are reviewed below.

Studies of Grain Boundary Effects and Grain Boundary Passivation

Ghandi *et al.* (1979) showed that grain boundaries shunting and diode leakage effects in polycrystalline GaAs Schottky barrier cells could be prevented by selective anodization. Polycrystalline GaAs films, 8 microns in thickness, deposited on molybdenum substrates by MOCVD (Metal Organic Chemical Vapor Deposition) were anodized in aqueous solutions of tartaric acid and ethylene glycol, such that, the relatively high localized

Table 2. Properties of thin-film GaAs and InP solar cells from Johnston (1979)

Cell Type	GaAs/AlAs	GaAs MOS	GaAs MOS	InP/CdS heterojunction
Deposition method	VPE	VPE	MOCVD	CVD
Typical grain size (microns)	3-5	3-5	1-3	1-3
Efficiency	--	6.3%	4.0%	5.7%
Open-circuit voltage (volts)	0.95	0.65	0.63	0.65
reference	Johnston and Callahan [1978]	Chu <i>et al.</i> [1978]	Johnston [1978]	Shay <i>et al.</i> [1978]

current at 'leaky' grain boundaries result in an insulating oxide barrier over the grain boundary, thus electrically isolating the grain boundary edge at the top surface from the Schottky barrier metal layer. Schottky barrier solar cells with 5.5% efficiency were demonstrated on such passivated GaAs films.

Cohen *et al.* (1980) probed the electrical potential in the vicinity of GaAs grain boundaries, as implied by shifts in the Auger electron spectra in order to determine the band bending due to the grain boundary. Their measurements indicated that the Fermi level was pinned by localized bandgap states due to dangling bonds of the grain boundary with the resulting band bending causing a double depletion region in the bulk material. Some types of grain boundaries resulted in "leaky" diodes, from which poor solar performance could be expected. However, some types of grain boundaries were benign, and did not appear to significantly affect the characteristics of Schottky barrier diodes that encompassed such grain boundaries. More detailed characterization of the electrical properties of polycrystalline GaAs films deposited on alumina ceramic and glass, confirming grain boundary defect trapping of minority carriers, was reported by Yang *et al.* (1980).

Kazmerski and Ireland (1980) compared solar cell performance for polycrystalline GaAs films grown by liquid-phase epitaxy (LPE) and molecular beam epitaxy (MBE). LPE-grown

cells showed better efficiencies, which they attributed to lower grain boundary activity from passivation by oxidation. Residual oxygen in the LPE growth system produced oxidation at grain boundaries during the growth process. Oxidation of grain boundaries was corroborated by Auger electron spectroscopy (AES), secondary ion mass spectrometry (SIMS), and x-ray photoelectron spectroscopy (XPS). Spencer *et al.* (1979) used deep-level transient spectroscopy to characterize grain boundaries in epitaxial layers of GaAs grown by MBE and LPE on poly GaAs wafers. They were able to attribute grain boundary depletion to an accumulation of native defects, enhanced segregation of impurities, and accumulation of copper from the substrates. Johnston *et al.* (1980) and Heller *et al.* (1980) improved the performance of polycrystalline GaAs liquid junction solar cells by diffusion of ruthenium into the grain boundaries of *n*-type poly GaAs films. They showed that grain boundary recombination can be reduced by such strongly absorbed impurities. The stability of such passivations was not reported. McPherson *et al.* (1980) observed strongly rectifying grain boundaries in poly GaAs bulk material with high intergrain resistivity, both of which could be reduced by diffusion of potassium. Tsuji *et al.* (1992) found similar debilitating grain boundary effects for GaAs films deposited on silica substrates by RF sputtering.

Surface Passivation

As might be expected, passivation of free surfaces, e.g., the GaAs-air interface, has some commonality with GaAs grain boundary passivation, where in both cases, the objective is to mitigate the deleterious electrical effects (minority carrier recombination) of defects associated with the surface or interface. Surface passivation techniques may also include treatments before application of metal contacts in Schottky barriers or ohmic contacts, or before application of insulating layers in MIS junction type devices. Unlike grain boundaries, free surfaces are accessible for post-growth passivation treatments and coatings. Techniques developed for surface passivation may nevertheless be applicable in some modified form to grain boundary passivation. Conversely, some aspects of grain boundary passivation may lend themselves to passivation of free surfaces, and it is worth viewing both surface and grain boundary passivation methods for a common perspective.

Kuroda and Ikoma (2001) investigated the passivation effects of antimony (Sb) and bismuth (Bi) on GaAs. Their specific interest was in applying 6-8 nm thick films of Sb and Bi as intermediate layers between the Au metal contact and GaAs in Schottky diodes. The Au/Bi/GaAs and Au/Sb/GaAs diodes showed substantially reduced reverse saturation currents and increased barrier heights. They attributed the passivation effects to termination of GaAs surface with Sb and Bi, reduction of oxides by Bi and Sb, and suppression of Au diffusion.

The year 1980 provides a good vantage point to assess the progress and perceived hurdles of low-cost III-V solar cells. The expansive Carter Administration funding for photovoltaics was coming to an end, and worldwide there was a shift in focus to thin-film amorphous silicon solar cells as the most-promising path for economic solar electricity. In retrospect, the amorphous silicon effort was perhaps an unfortunate diversion that

cost the solar industry a decade of progress, although technology development for making large monolithic modules by way of thin-film deposition on glass substrates for amorphous silicon solar cells and flat panel displays would benefit other types of low-cost solar cells as well. A substantial R&D effort exploring the potential of thin-film polycrystalline III-V solar cells at Rockwell International (with Cornell University, Howard University, and North Carolina A&T University), AT&T Bell Laboratories, MIT Lincoln Labs, Southern Methodist University, Jet Propulsion Laboratory, and IBM had come to a close. There was a consensus on the crucial problems that needed to be solved for thin-film poly-GaAs and other III-V solar cells. Many of the recommendations made at that time framed research efforts for the next two decades, although at a much less intense level of activity. To what extent these problems have been adequately addressed, or 'designed around' is an objective criteria to assess progress and current prospects.

The Rockwell International group (Miller *et al.* 1981) summarized the situation as follows:

1. It is unlikely that very large grain (~mm) thin-film GaAs will be achieved on foreign substrates using current methods.
2. Rapid diffusion at grain boundaries will necessitate relatively low deposition temperatures.
3. Grain boundaries fall into two distinct categories: benign and catastrophic or fatal. The benign grain boundaries have little band bending associated with them, while the fatal grain boundaries behave as Schottky junctions with barrier heights of ~1 eV. Even a small number of such grain boundaries significantly reduces overall solar cell performance.

The Rockwell International group further offered the following recommendations:

1. Efforts should focus on eliminating the adverse effects of grain boundaries, either through passivation or elimination of the grain boundary.
2. Efforts in materials development should be directed to achieving single-crystal or nearly-single crystal GaAs thin films on low-cost substrates—using for example graphoepitaxy or laser recrystallization—or by film transfer techniques with re-usable substrates.
3. Efforts for grain boundary passivation effects should be correlated with studies on GaAs free surfaces. Grain boundary isolation methods may also be feasible.

In the following, we review work that focused on these challenges, either with specific application to GaAs solar cells, or in different contexts not directly related to solar cell applications.

III-V SEMICONDUCTOR FILMS ON DISSIMILAR SUBSTRATES

Films of III-V semiconductors directly deposited on crystallographically dissimilar substrates such as metal foils or amorphous substrates such as glass typically exhibit average grain sizes of around 1-10 microns. Stocker *et al.* (1970) deposited polycrystalline GaAs films on sapphire substrates using an open-tube AsCl_3 -Ga- H_2 vapor transport technique, yielding grain sizes of about 1 micron. Interestingly, such material still exhibited room-temperature photoluminescence, despite the small grain size. Without dramatic improvements in methods of passivating grain boundaries, this microstructure will not support a high-efficiency solar cells. The required grain size will depend on the device design and passivation methods, but even grain sizes in the range of several hundred microns may not be sufficient. Vernon *et al.* (1979) achieved average grain sizes of 0.2 mm in GaAs thin films on metal substrates, but the solar cells

made in such material were still plagued by low open-circuit voltages and fill factors. Based on the electrical behavior of grain boundaries in typical poly GaAs films, grain sizes of at least 1 mm are probably needed. Methods of controlling deposition conditions to yield enhanced grain sizes would therefore constitute an important development in III-V thin-film photovoltaics. Work on crystal growth of semiconductors on amorphous substrates, with emphasis on silicon, has been reviewed by Givargizov (1991), particularly methods of *grapho-epitaxy* where the substrate is structured to induce a preferred alignment of nucleated crystals from a liquid phase. Other approaches involve some method of controlling the density of nucleation sites from the vapor-phase, which ultimately determines grain size, and possibly controlling the orientation of the nucleated crystals to yield low-angle grain boundaries which are less electrically active. Some of the work that is specific to III-V semiconductors with relevance to solar cells is described in more detail below.

Post-deposition recrystallization is often a key step in thin film silicon polycrystalline solar cells, where silicon layers deposited on a substrate, such as ceramic, glass, or quartz, are melted and recrystallized in order to enlarge grains. As described below, a similar recrystallization process applied to germanium films serving as seeding layers for GaAs epitaxy proves a valuable approach to thin-film III-V solar cells. Relatively little has been reported on recrystallizing small-grain polycrystalline III-V semiconductor films with the aim of increasing grain size, particularly for solar cell applications. Li *et al.* (1985) deposited 1-2 micron thick InP films on oxidized silicon by sputtering, followed by laser recrystallization (5.8 to 7 W, beam diameter 70 microns). The irradiated InP layers showed single-crystal electron diffraction patterns and carrier mobilities of $10^3 \text{ cm}^2/\text{V}\cdot\text{s}$. Ridgeway *et al.* (1991) made studies of the solid-phase epitaxial growth of amorphized InP at temperatures of 145-335 °C, but since this method relies on an InP substrate, it has little

direct interest to low-cost III-V solar cells. Recrystallization of deposited III-V semiconductor films in order to increase grain size is problematic due to the decomposition of the material related to the high volatility of the Group V element. Encapsulating the III-V semiconductor layer can reduce decomposition of the III-V material during high-temperature processing. Iida (1985) reported a somewhat complicated method of forming single crystal films of InP on glass substrates, using a molecular deposition technique in combination with recrystallization and liquid-phase epitaxy. An 8-micron thick InP layer is deposited on glass, and then is capped with a 20-micron thick layer of molten In to suppress evaporation of P, with all steps performed at below 300 °C. The composite layered structure is slowly cooled to around 80 °C, then rapidly heated to 1000 °C for a few minutes, and cooled again to room temperature. Iida reported that Laue x-ray patterns and double-crystal X-ray rocking curves suggested single-crystal films of 1-cm x 1-cm in extent could be achieved, although in some areas an over- or under-layer of polycrystalline InP may also be present. Kanata *et al.* (1988) performed a series of experiments on the solid-phase recrystallization of GaAs on silicon dioxide/tantalum/nickel substrates. These studies including recrystallization of substrates with a relief pattern to induce grapho-epitaxy. The resulting grain size is roughly equal to the feature size of the surface relief, which in this case is about 1 micron.

The dynamic control of nucleation sites and density in CVD, a process called SENTAXY (Selective nucleation based epitaxy), was introduced by Kumoni *et al.* (1989) to enhance grain size on silicon CVD layers on amorphous substrates. Growth conditions are programmed so that small clusters of silicon atoms (embryonic nuclei) formed in the early stages of growth disappear, leaving the sparser large clusters to emerge and sustain as grains. Yonehara (1997) has described SENTAXY with potential application to silicon solar cells. Tokunaga *et al.* (1992) developed

an analogous selective vapor-phase deposition process to control nucleation and resulting grain structure of GaAs on oxidized silicon substrates, in which case the oxide-coated silicon simulates an amorphous substrate. First, a low density of silicon crystallites are deposited on the oxide surface by low-pressure CVD with a silane precursor, where the supersaturation and substrate temperature control the spacing of silicon nuclei. The discrete silicon crystallites are used to seed the growth of GaAs by MOCVD. Although the GaAs is still polycrystalline, the size and texture of the grains represented material of substantially higher quality—as assessed by room-temperature photoluminescence—compared to GaAs deposited directly on oxide coatings with no selective silicon nucleation sites. Small-area (16-micron diameter) LEDs with room-temperature luminescence intensity of 1 microwatt (optical power output) at 1 mA drive current were fabricated in this material. Demonstration of room-temperature LED operation is a good indicator of material quality suitable for photovoltaics applications.

Jones *et al.* (1999) investigated the MOCVD of GaAs directly on molybdenum foils. Grain sizes in the range of 1-2 microns were achieved, and the GaAs films showed a high density of defects. These characteristics appeared to be very dependent on growth temperature. Imaizumi *et al.* (2000) used a chemical beam epitaxy system to grow polycrystalline films of GaAs on quartz substrates at temperatures of 400 to 500 °C. Grain sizes were limited to 0.5 to 1.0 microns, with high resistivity and low carrier mobilities. Allen *et al.* (2005) developed a method for selective nucleation of GaAs on silicon. As it is feasible to grow monocrystalline GaAs epitaxial layers on single-crystal silicon wafers, the value of this work is in translating the method to cheaper, crystallographically dissimilar substrates. Nucleation sites at submicron holes are defined in a photoresist layer coating a silicon wafer. Ga is electrochemically deposited in the holes. Annealing in arsine (AsH₃) converts the selectively-deposited Ga into GaAs. The crys-

tals are then enlarged toward coalescence using MOCVD. Yi *et al.* (2001) achieved oriented growth of GaSb on a patterned amorphous substrate by metal organic chemical vapor deposition. The Si substrate was patterned with an array of inverted pyramids using lithography and anisotropic KOH etching and then the surface, and a thin (5 to 8 Å) amorphous SiO₂ films was then formed on the surface by boiling in an HCl:H₂O₂:H₂O solution. Strongly-oriented GaSb crystals were induced with this substrate surface relief, although there would seem to be the possibility of seeding by the underlying silicon through pinholes in such a thin oxide layer. More generally, this work supports the feasibility of graphoepitaxy methods to III-V materials.

A wide variety of processes have been investigated for depositing III-V semiconductor films on dissimilar substrates. Barnett *et al.* (1984) described a metallic solution growth process, akin to liquid-phase epitaxy, for depositing thin films of GaAs on dissimilar substrates such as steel and quartz, with application to solar cells. Qia *et al.* (2009) co-evaporated Ga and Sb to form poly-GaSb on glass substrates. Although the grain size was small (0.5 microns), hole concentrations of 10¹⁷ cm⁻³ and hole mobilities of 130 cm²/V-s suggested some promise for thermophotovoltaics. Milnes and Feucht (1976) suggested a process called *rheotaxy*, first described by Rasminis in 1963 for the growth of silicon layers on ceramic glazed with oxide compounds which are fluid at the temperature of Si growth, might also have potential for producing large-grain III-V films on low cost substrates. They explored the growth of III-V films from the vapor-phase on substrates coated with a molten metal, GaSb, or InSb layer, but this technique has not been given much subsequent attention. More recently, Branch *et al.* [2008] developed a low-cost vector-flow epitaxy for AlN that employs atmospheric pressure growth, maintains separation of the gaseous reagents in the growth chamber, and uses pre-cracking of the group V precursor to reduce the V/III ratio

required for III-V nitride growth. Dhakal *et al.* (2009) described electrodeposition of AlSb on mesoporous TiO₂ on indium tin oxide for solar cell applications. AlSb, with a bandgap of 1.62 eV, is not normally considered for terrestrial solar cells due to difficulty in its synthesis by CVD or LPE and its hygroscopic nature. However, points in its favor include its high absorption coefficient, allowing efficient thin film absorbers, and the plentifulness and low cost of both Al and Sb. Sherohman *et al.* (2007) discuss aluminum antimonide for solar cell applications. Some previous work on magnetron sputtering and annealing of AlSb polycrystalline films showed grain sizes of 20 nm (Chen *et al.* 2006). Analogous methods for other III-V semiconductors could help make III-V solar cells more economical.

More recent work by Jones *et al.* (1998) on CVD grown III-V semiconductor thin films investigated the microstructure of GaAs films formed on molybdenum substrates by metal organic chemical vapor deposition (MOCVD). Grain size increased with growth temperature, but average grain sizes were less than 2 microns, and there was a high density of intragrain defects (Imaizumi *et al.* 2000). Friedman *et al.* (1997) used molecular beam epitaxy to deposit polycrystalline GaAs, but concluded that while solar cell photocurrent could be enhanced somewhat by optimizing growth temperature and III/V flux ratio, it was unlikely that material quality (could be achieved without a substrate that could serve as a template for large-grain sizes. Tokunaga *et al.* (1992) produced discontinuous polycrystalline GaAs films on silica-coated silicon substrates, by first depositing and patterning a regular array (islands centered on 10 x 10 um centers) of silicon seeding islands, followed by selective MOCVD of GaAs. Some degree of control of grain size was gained by controlling the silicon island area. Smaller silicon seeding islands yielded larger average grain sizes in the GaAs overlayer.

Interestingly, some devices made in other III-V semiconductors appear to tolerate small grain

sizes in device applications, or are more amenable to achieving larger grain sizes. Qiao *et al.* (2009) formed polycrystalline GaSb films on glass substrate by co-evaporation of Ga and Sb. Although average grain sizes were only about 0.5 microns, the optical properties and carrier mobilities suggested the as-deposited GaSb material might be adequate for thin-film thermophotovoltaic applications.

A somewhat different approach is to develop new substrate materials that simulate single-crystal wafers. Norton *et al.* (1997) reported on methods of producing metal sheets formed without large-grain boundaries using RABiTS (rolling-assisted biaxially textured substrates). For example, nickel rod can be cold-rolled into a sheet and annealed, yielding grain sizes of 50-100 microns. This technology has been developed for high-temperature superconductors, and the authors speculated on its application for solar cells, noting a host of problems, such as chemical compatibility, that would need to be addressed. Along similar lines, Goyal *et al.* (1997) considered the feasibility of using oxide buffer layers atop large-grain metal sheets for use as substrates for epitaxial growth of GaAs and Si. Some suggested multilayer structures included CeO_2/Ni , YSZ (yttrium stabilized zirconium) / CeO_2/Ni , and $\text{MgO}/\text{Ag}/\text{Pd}/\text{Ni}$. Exploratory research on candidate materials for alternative substrates has assessed the quality of the substrate material grown as a layer on a GaAs substrate.

The recent development of single-crystal-like germanium layers on flexible metal substrates with oxide intermediate layers is noteworthy. As discussed in the next section, germanium buffer layers on low-cost substrates can seed the epitaxial growth of GaAs and related compounds; the utility of the Ge buffer layer is that it is amenable to recrystallization to attain large grain films. As Ge is lattice-matched and thermal-expansion-matched to GaAs, a Ge-coated metal substrate can effectively replace the expensive GaAs wafer. The approach described by aUniversity of Houston/

SuperPower (Schenectady, NY) (Selvamanickam *et al.* 2010; Freundlich *et al.* 2010) achieves as-grown single-crystal films of Ge and GaAs on metal substrates, without a recrystallization step. A MgO film is deposited on a flexible hastelloy metal substrate by ion-beam assisted deposition, followed by a film of CeO. A 6-micron thick Ge film grown on the oxides functions as a single-crystal-like template for subsequent GaAs epitaxy. The single-crystal nature of the Ge films was corroborated by RHEED, X-ray diffraction, and transmission electron microscopy. These coatings are made in reel-to-reel continuous processing compatible with high-throughput manufacturing. GaAs films grown by MBE on these composite metal/oxides/Ge substrates showed strong photoluminescence.

RECRYSTALLIZATION OF GERMANIUM FILMS FOR GAAS EPITAXY

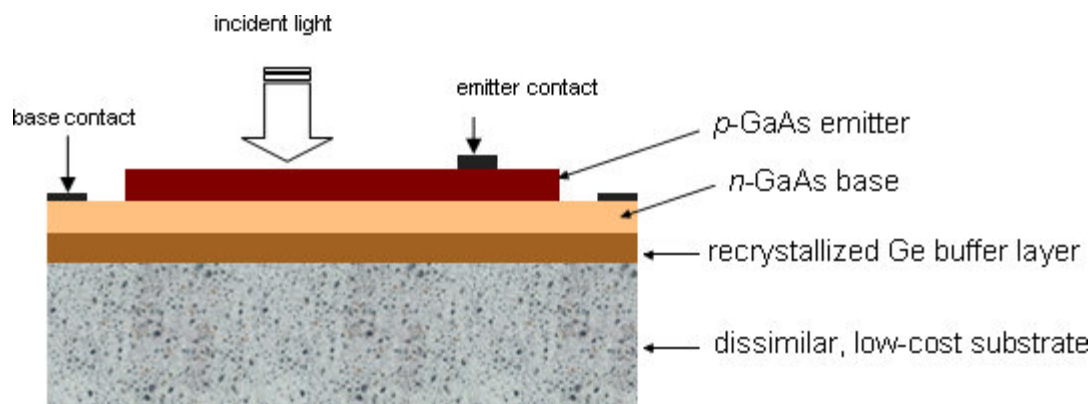
Germanium proves to be a very suitable substrate for GaAs solar cells. Ge is closely lattice matched and thermal expansion matched to GaAs and AlAs. High-efficiency GaAs solar cells can be grown on Ge substrates. In fact, triple-junction GaInP/GaAs/Ge solar cells grown on a Ge substrate have the highest efficiencies of any solar cell (see Table 1). Ge is relatively expensive and scarce, and solar cells based on Ge wafers would offer no dramatic long-term cost benefits over solar cells based on wafers made from III-V bulk crystals. The utility of Ge is as an intermediate buffer layer between a low-cost substrate and the GaAs solar cell device structure. The key step is recrystallization of the deposited Ge layer to increase its grain size. The large-grain Ge layer seeds the epitaxial growth of a GaAs overlayer. The epitaxial GaAs layer(s) replicates the grain structure of the Ge buffer. Thus, GaAs films with large grains can be produced on a variety of inexpensive substrates. A very basic schematic of this approach is shown below.

This idea dates from the mid-1970s, and there has been some notable progress in making >10% efficient GaAs solar cells on cheap substrates coated with Ge. Yeh *et al.* (1978) measured an 8% efficiency on a solar cell made on CVD GaAs/recrystallized germanium-on-tungsten substrate. Techniques for achieving “device-quality” polycrystalline GaAs on Ge-coated molybdenum substrates by CVD were elaborated by Pande *et al.* (1979) using trimethylgallium and arsine precursors for GaAs and germane for Ge. This work did not include a germanium recrystallization step, and grain sizes were in the range of 5-15 microns. These workers noted that despite the very close lattice match between GaAs and Ge, inter-diffusion, cross-doping, and other chemical compatibility issues necessitated careful control of the GaAs on Ge epitaxy process. The later results demonstrating record high-efficiency GaAs/Ge solar cells by MOCVD prove this is a manageable problem, at least for MOCVD. Chu *et al.* (1986) reported GaAs solar cells made by first depositing a 10-micron thick layers of Ge on tungsten-coated graphite substrates by thermal

reduction of GeCl_4 . The Ge layer was recrystallized using a moving strip heater to yield elongated Ge grains up to 1 mm in width and 5-10 mm long. $p^+/n/n^+$ GaAs homojunction solar cells were grown on the recrystallized Ge layers by chloride vapor-phase epitaxy. Solar cells of 1-cm² area fabricated on this material achieved efficiencies of 10.3%. Shinoda *et al.* (1983) used a similar approach to produce GaAs LEDs on oxide-coated silicon through the use of a tungsten coating of the oxide, deposition of 0.4- μm of Ge, and recrystallization of the Ge, followed by epitaxial growth of p - n homojunction GaAs LED.

The ultimate potential of this approach, i.e., using a large-grain Ge buffer layer, is underscored by Venkatasubramanian *et al.* (1997) in work demonstrating a 20% efficient AlGaAs/GaAs solar cell on sub-millimeter grain size multicrystalline Ge wafers. Optical-grade polycrystalline Ge wafers were used as substrates for MOCVD of an AlGaAs/GaAs heterostructure. This relatively sophisticated six-layer epitaxial structure (total thickness = 5 microns) included an undoped GaAs spacer layer between the emitter and base

Figure 2. Recrystallized germanium layer serves as a buffer layer to seed the epitaxial growth of GaAs solar cell. Shown here is a simple, p - n homojunction, but in principle, more complicated, multilayer heterostructure solar cells involving GaAs and lattice-matched compositions of InGaP and AlGaAs are also possible. The Ge buffer could also function as the low-bandgap bottom cell of a multi-junction solar cell stack. Depending on whether the substrate is an insulator (e.g., ceramic, glass, or quartz) or a conductor (e.g., metal foil, highly-doped silicon), the base contact may be through the substrate or from the top side.



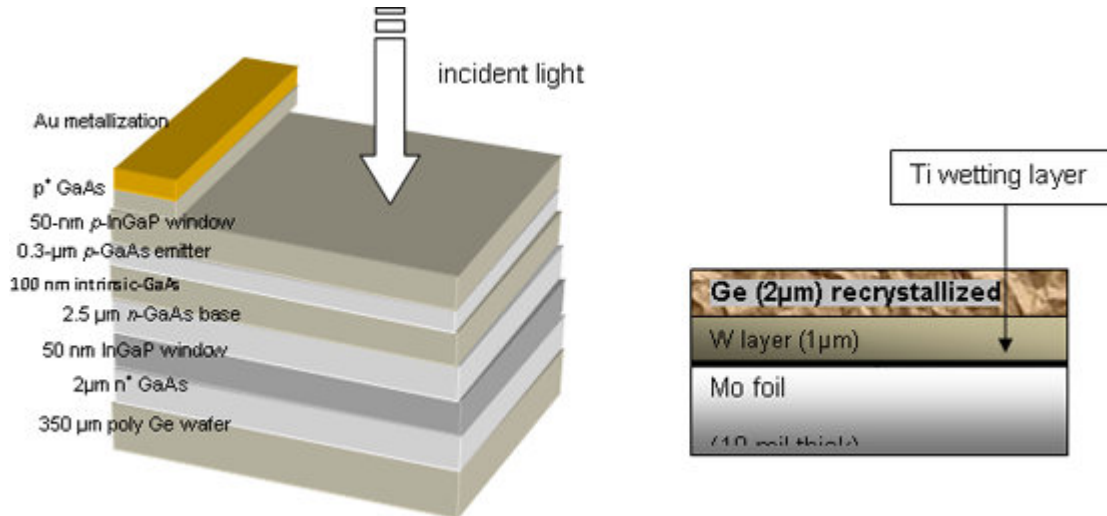
to suppress dark currents otherwise exacerbated by high defect densities. This same group reported some preliminary work on growing Ge on glass or molybdenum as a pathway to GaAs solar cells on low-cost substrates, using the solar cell design tried with poly Ge wafer substrates. The significance of this work is that presumably a recrystallized Ge layer (with comparable grain structure) on a cheap substrate could substitute for the poly-Ge wafers, leading the way to a high-efficiency, thin-film polycrystalline GaAs solar cell, and in fact, this work revived interest in low-cost thin-film poly-GaAs as a candidate for low-cost, high-efficiency solar cell. NASA (Glen Research Center) has investigated the use of poly GaAs on poly Ge deposited on flexible metal foil or polymer substrates for light-weight, compactly stowable space solar cells (Wilt 2006). As a first step, they developed single-junction GaAs *p-i-n* solar cells with InGaP front and back cladding layers on polycrystalline Ge wafers with grain sizes on the order of millimeters, but the cells were limited to an estimated efficiency of 13% by an unintended junction formed at the GaAs/Ge interface (Wilt *et al.* 2007). Solar cell results on Ge/W/Ti/Mo foil substrates were reported by Bailey *et al.* (2008). Figure 3a shows the basic test device structure grown on commercial poly Ge wafers (100 μm^2 average grain size). Figure 3b shows the metal foil substrate structure for the test device. The Ge layer is annealed post-deposition at 675 °C in hydrogen to promote grain growth and improve crystallinity. The test device on poly Ge wafers exhibited about 17% efficiency, but when grown on the molybdenum foil substrate showed only about 4% efficiency, which is attributed to the small grain size and rough surface morphology in the case of the metal foil substrate. Bailey *et al.* (2008) suggest a possible remedy is the use of textured polycrystalline Ge layers, deposited epitaxially using a series of metallic buffer layers, to improve this situation. Techniques along these lines using evaporated Ge layers (2 to 3.4 μm thick), W/Ti and Cr adhesion layers and various

annealing regimens, achieving grains with lateral dimensions on the order of 100 μm were described by Polly *et al.* (2009). In a similar effort, the recrystallization of amorphous Ge films deposited by RF sputtering on 25- μm thick molybdenum foils was studied (McNatt *et al.* 2009), achieving grain sizes as large as 0.5 cm^2 . Understanding the differences in thermal expansion coefficients between Ge and various metals comprising the substrate was a key aspect of this work.

Methods of Achieving Large-Grain Ge Films on Dissimilar Substrates and Applications to GaAs Thin-Film Solar Cells

The ability to recrystallize Ge—yielding millimeter-size grains—is remarkable, especially in view of the relative difficulties encountered with analogous processes applied to silicon and compound semiconductors. Germanium is expensive, and consequently there is great incentive to develop recrystallization processes that can be applied to thin (1 micron or less) layers. Thin films of molten germanium will tend to agglomerate and therefore in many cases the Ge layer is capped with an inert layer to maintain the integrity of the planar Ge coating in the molten state. Wetting angles and surface tensions of $\text{Ge}_{1-x}\text{Si}_x$ melts on different substrates (fused quartz, BN, AlN, Si_3N_4) have been measured by Cröll *et al.* (2004). A simple solar cell structure is afforded by using a metal or other conducting substrate, as the substrate can then serve as the back ohmic contact for the cell. This presumes that a non-rectifying, low-resistance current-voltage characteristic can be achieved between the substrate and deposited layers. Alternatively, while an insulating substrate such as a ceramic complicates the contacting of the backside of the solar cell, it facilitates various all-top-contact, interconnection schemes where an array of smaller, electrically isolated solar cells are formed, by for example etching through the device layers to the insulating substrate, and then

Figure 3. (a) NASA (Glenn Research Center) solar cell test structure, and (b) low-cost Mo foil substrate with Ge buffer layer for thin-film GaAs space solar cells. After Bailey *et al.* [2008].



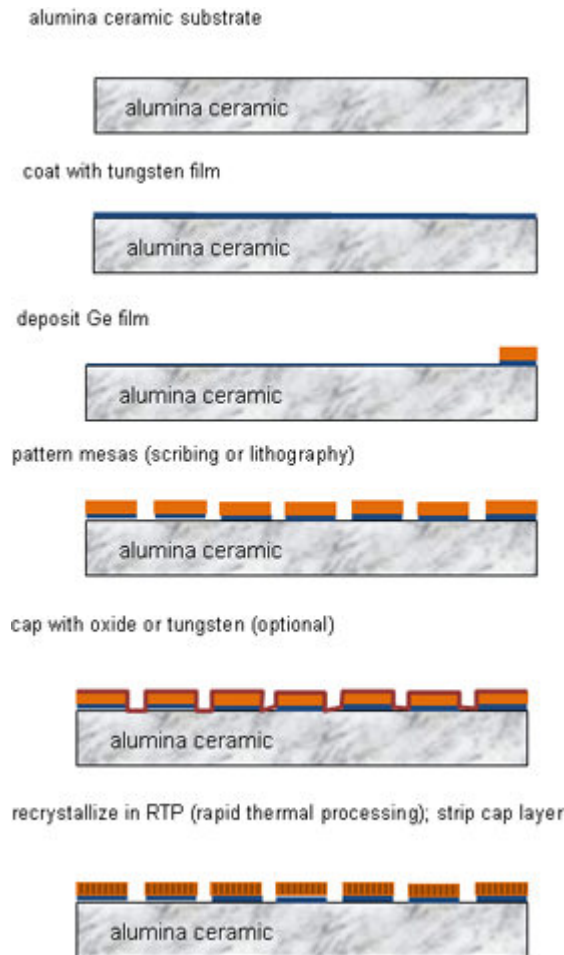
connected in series to achieve higher voltages. In this case, the insulating nature of the substrate is a definite advantage. With metal substrates, an additional electrical insulating layer would be needed to simulate an insulating substrate. Monolithic series-connected GaAs solar cells generating open-circuit voltages of 4 V, have been demonstrated (Borden *et al.* 1980; Masu *et al.* 1981). These designs take advantage of the availability of semi-insulating GaAs substrates (such semi-insulating substrates are generally not available for many other solar cell materials systems), and presumably similar approaches would be feasible with GaAs solar cell structures formed on other types of electrically insulating substrates.

Mauk *et al.* (1999) described a device topology wherein a germanium film is deposited on an alumina ceramic and then isolated into a regular array of mesas with trenches formed by etching or scribing (Figure 4). The Ge is then capped with tungsten to prevent agglomeration, and recrystallized in a rapid thermal annealing system (as seen in Figure 4). The Ge mesas (typically ranging in area from 0.5-mm x 0.5-mm to 1-mm x 1-mm) are often single-crystal or comprised of just a few grains (as seen in Figure 5). This array of Ge

seeds the selective epitaxy of a GaAs-based solar cell after etching off the tungsten cap. In epitaxial growth under sufficiently low supersaturation, there is no nucleation or deposition of GaAs in the trenches. The solar cell mesa elements could be series-interconnected to form a monolithic submodule. Although some active area is lost due to the isolation trenches, this area could be used for the metallization lines that inevitably shade the solar cell to some degree. Also, it is feasible to largely mitigate this active area loss with a lensed array or prismatic coverslip (Figure 6) that refracts light away from the isolation trenches, as is done to avoid grid shading losses in more conventional solar cells—see for example Boca *et al.* (2009) and Jaus *et al.* (2010).

In this design, internal grain boundaries are traded for increased cell perimeter (as shown in Figure 7). Edge or perimeter recombination has been shown to be significant in GaAs solar cells, mainly through increased dark current which leads to lower open-circuit voltages (Henry and Logan, 1978; Stellwag *et al.* 1990a,b). The perimeter current is exacerbated as the area of the mesas is reduced. Although in many regards, grain boundary recombination is similar to perimeter (or free

Figure 4. Process for forming an array of GaAs solar cell mesas on a ceramic substrate

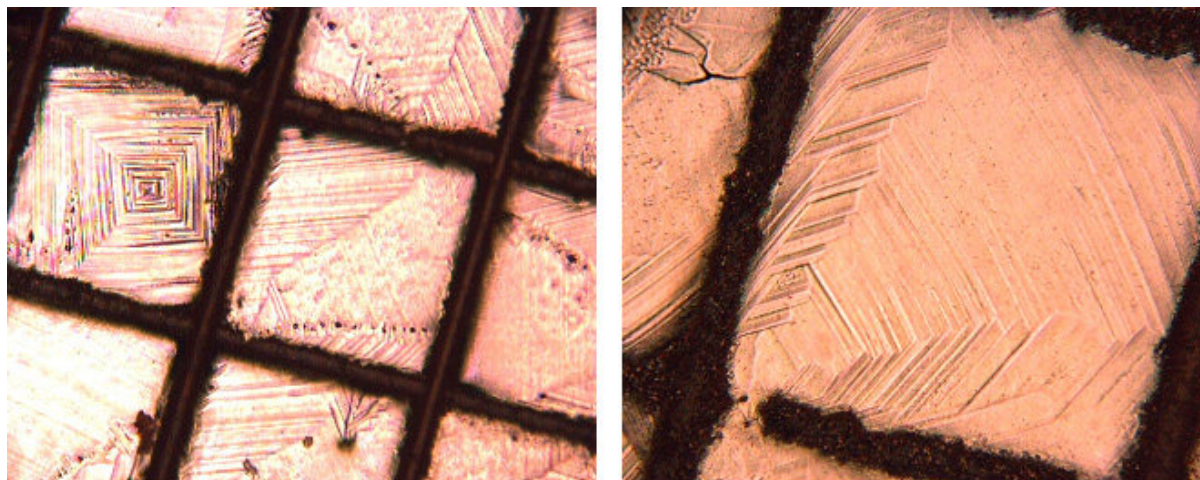


surface) recombination, recombination at free surfaces can be very effectively reduced by the use of lattice-matched, wide-bandgap cladding or window layers. In fact, the use of lattice-matched heterostructures for minority carrier confinement and reduction of surface recombination is one of the key enabling features of GaAs-based semiconductor devices, including solar cells. Kurtz and McConnell (1997) made a very informative modeling study of the effect of free surface (including perimeter) vs. bulk (grain boundary) recombination on GaAs solar cell efficiency, as summarized in Figure 8. If grain boundaries could be as effectively passivated (i.e., rendered to a

comparable low level of minority carrier recombination) as free surfaces are with wide-bandgap AlGaAs cladding layers, grain sizes of 20-50 microns would suffice to achieve 20% conversion efficiency. As surveyed below, this grain size appears feasible, but the extent to which free-surface passivation methods can be applied to grain boundaries is uncertain.

The mesa array design is based on the premise that small mesas can be formed without—or at worst a few—grain boundaries. The penalty is a loss of active area due to the isolating trenches between adjacent mesas, and the increased perimeter recombination of the mesa solar cells. The loss in active area could be mitigated by utilizing the trenches for grid metallization, and using refractive cover slips to bend light away from the trenches onto the mesas. The increase in junction perimeter to reduce grain boundary effects is a favorable trade-off, since free surfaces such as junction perimeters can be effectively passivated, while methods for highly-effective grain boundary passivation in GaAs remain elusive. Additionally, Yamaguchi (1991) showed that reduction in epilayer coverage of GaAs on silicon, where the GaAs is isolated as mesas, could provide dramatic reductions in thermal stress and dislocations (as measured by etch pit density), when the lateral dimensions of the mesa were less than 100 microns. Presumably, the improvement in material quality with growth area reduction—either by selective growth through openings patterned in a masking layer covering the substrate, or by post-growth patterning with isolation trenches—is related to a reduction in stress effects due to thermal expansion and lattice mismatch. As the alumina substrate is better thermal match to Ge and GaAs, than GaAs is to silicon, this effect may be operative for even larger (100 microns to > 1 mm) GaAs/Ge mesas on alumina. Figure 9 shows various mesa geometries and the degree to which junction perimeter is exposed and free surfaces can be passivated. Whether practical epitaxial growth methods could reproducibly achieve these

Figure 5. Recrystallization of germanium on alumina ceramics. These 1-mm x 1-mm islands showed one or just several grains.



‘wrap-around’ wide-bandgap layer cladded structures is not certain.

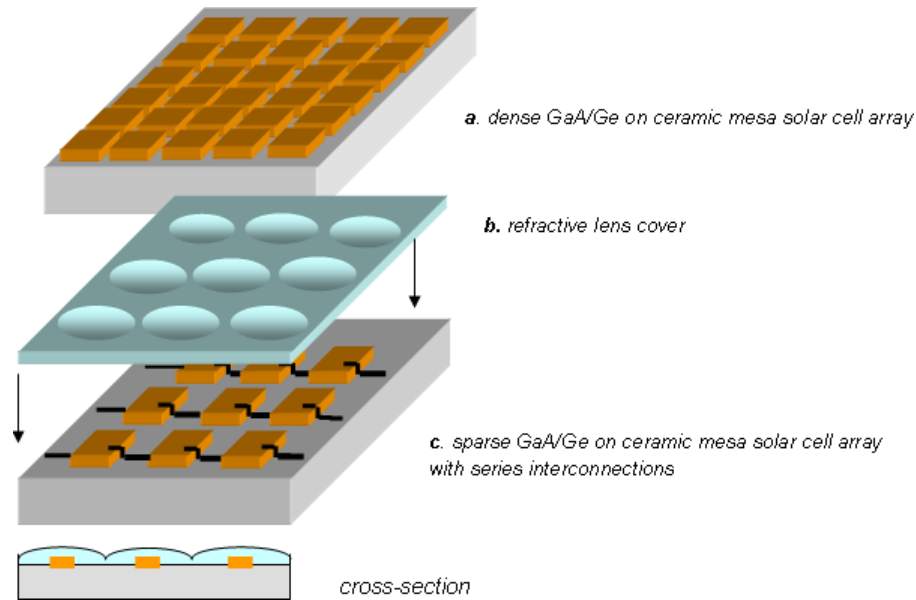
The use of recrystallized Ge buffer layers for seeding the epitaxial growth of GaAs solar cells supported on a low-cost substrate such as ceramic or metal foil solves several problems by mitigating grain boundary effects and allowing a wider range of candidate substrates. The main objective is to achieve large grain structures in as thin a Ge layer as possible. Some secondary issues include texture (i.e., predominant orientations of the grains), grain aspect ratios (e.g., elongated grains), grain boundary angles, chemical compatibility, and whether Ge buffer layer itself could support a low-bandgap bottom solar cell as part of a multi-junction tandem stack solar cell. Some methods of forming Ge films on dissimilar substrates, with potential relevance to III-V solar cells are reviewed below.

Kurov *et al.* (1963) evaporated Ge films, with thicknesses of 4-20 microns, on substrates of different materials (quartz, graphite, steel), and studied the effect of temperature and substrate material on the size of Ge crystals. In some cases, millimeter-size grains were achieved by post-deposition recrystallization. This was one of the

earlier works showing large-grain Ge films could be formed on dissimilar substrates, and represents a favored approach of melting the deposited Ge layer and resolidifying it to achieve larger grains. A related graphoepitaxy method for forming germanium layers on a SiO_2/Ta -coated nickel replica substrate impressed with a surface relief from a pyramidally-texture etched silicon wafer was reported by Kanata *et al.* (1989). The Ge is grown from a molten Ge-metal eutectic by scanning laser melting/recrystallization. Ge crystallite sizes of 2-10 microns were achieved.

Barná *et al.* (1972) studied nucleation and crystal growth rates in thermally-evaporated amorphous germanium films deposited on SiO_x -coated substrates, and in particular, characterizing nucleation rates as a function of temperature and time. This represents an alternative approach of solid-phase recrystallization of an amorphous or fine-grained deposited Ge film in order to enhance grain size. Herd *et al.* (1972) added a metal contacts to the amorphous germanium film to induce nucleation, and add a degree of nucleation site control in order to reduce nucleation density and achieve larger grains. The solid-phase recrystallization process was combined with graphoepitaxy

Figure 6. Scheme illustrating one possible application of small (Al)GaAs solar cells formed on ceramic for use with refractive lens concentrators



on SiO_2 substrates with a 0.2- μm period relief grating (Yonehara *et al.* 1984). Solid-state, surface-energy-driven grain growth produced a preferred orientation in 30-nm thick Ge films. Similar metal-induced selective solid-phase crystallization as developed by Yang and Atwater (1996). In this approach, metal islands were deposited on top of a 50-nm thick amorphous germanium film to control grain size and location. Ge grain sizes as large as 50 microns were achieved at temperatures less than 475 $^\circ\text{C}$, although it appears that many much smaller grains were interdispersed among the larger Ge grains.

Klykov and Sheftal (1981) achieved single crystal layers of Si and Ge, with an area of about 15 mm^2 , on fused quartz substrates that featured a micro-relief for graphoeptiaxy, and using a vapor-liquid-solid (VLS) growth process. In VLS growth, the germanium deposits from a molten layer of metal, e.g., 15 microns of gold), that is supplied via the vapor-phase by reduction of GeCl_4 . The orientation of crystals nucleated from the molten metal phase is due to capillary forces

that align the crystallites along features of the microrelief. A graphoeptiaxy approach based on recrystallizing 0.5-micron thick evaporated Ge films on quartz substrates with a square-wave or saw-tooth surface relief gratings yields Ge crystals ~ 3.5 microns by several hundred microns in size (Geis *et al.* 1982). Nishioka *et al.* (1984) studied the crystallographic orientation of electron-beam deposited, 300-to 400-nm thick laser-recrystallized Ge films on quartz substrates.

Zone-melting Ge film crystallization was reported by Ohmachi *et al.* (1983). These workers crystallized 0.4 to 0.8 micron thick Ge films on W-masked, oxidized silicon wafers. The Ge layer was capped with another layer of W. The capped Ge was recrystallized with a moving (1 mm/s) strip heater. The W cap can be selectively stripped from the recrystallized Ge layer. Single-crystal Ge regions, 100 microns wide and several millimeters long, were achieved. As an alternative to heating for recrystallization of Ge, Som *et al.* (2008) demonstrated room-temperature recrystallization of amorphous Ge films (produced by

Figure 7. Control of grain structure by selective growth of GaAs mesas

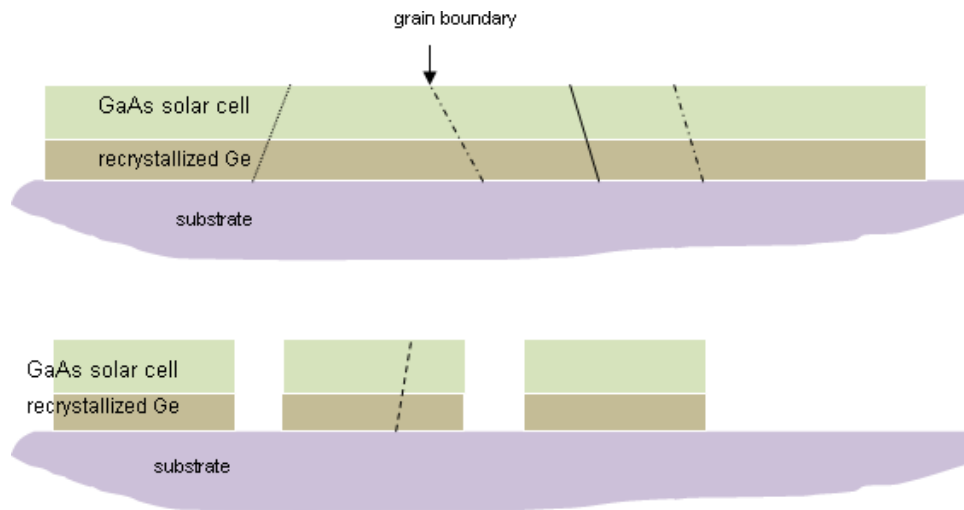


Figure 8. Modeling showing the effect of grain boundary size and surface passivation on GaAs solar cell efficiency. The bottom curve (Yamaguchi) shows the efficiency assuming a typical model for grain boundary recombination and its effects on voltage, current, and fill-factor. The top curves indicate the efficiencies expected if the perimeter recombination of a grain were as low as that achieved for external GaAs surfaces (e.g., using an AlGaAs passivating layer). RTI data refers to GaAs solar cells grown on multicrystalline Ge wafers (grain size approx. 1 mm), see Venkatasubramanian et al. (1997); After Kurtz and McConnell (1997).

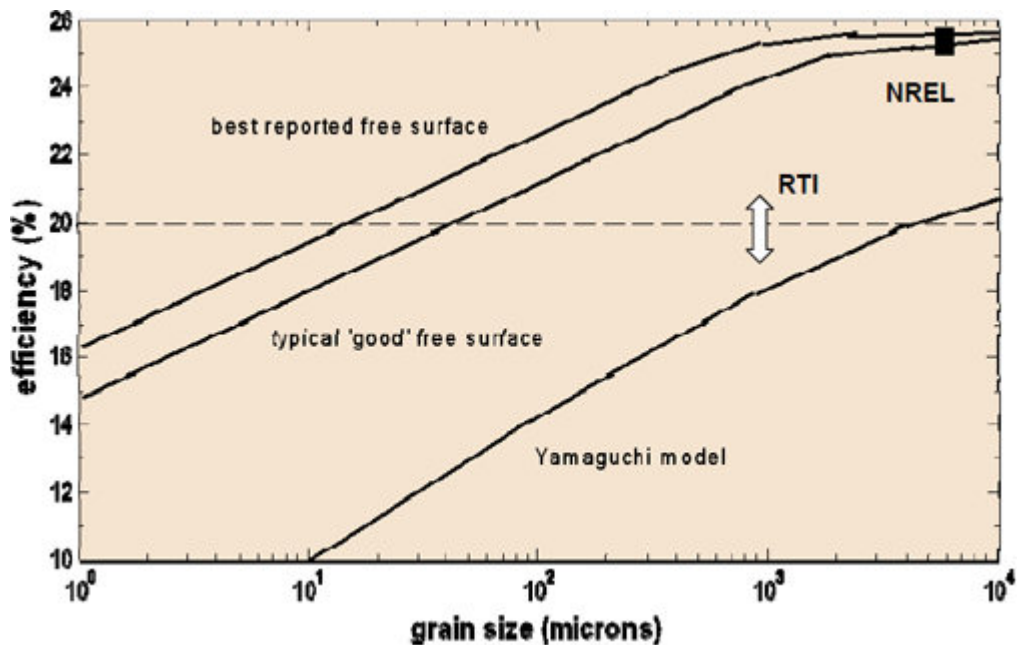
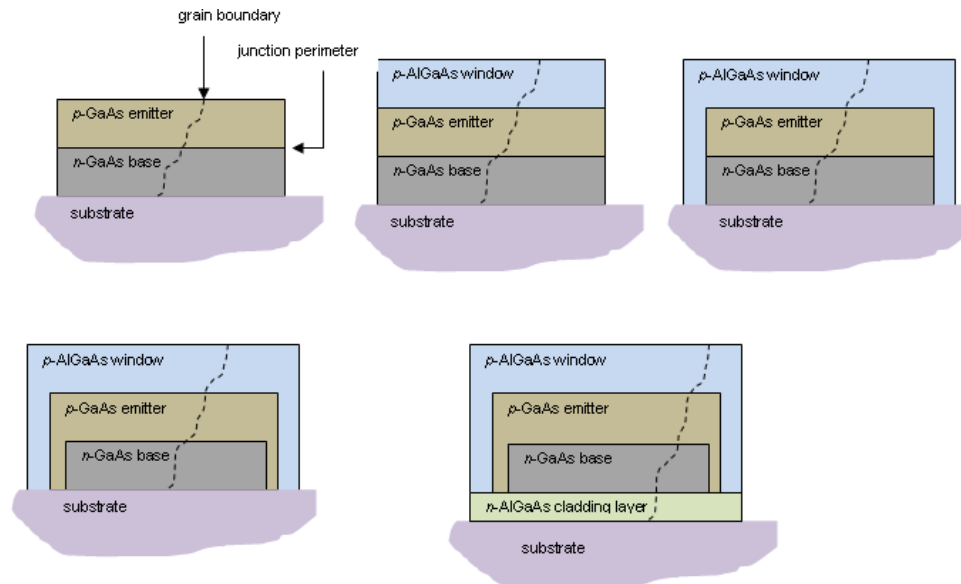


Figure 9. Edge and grain boundary exposure and methods of passivation. Grain boundaries are not accessible to passivation. Forming the solar cell as small mesas decreases the internal grain boundaries (which are difficult to passivate), but increases external surface area (which can be effectively passivated by, for example, lattice-matched wide-bandgap cladding layers).



irradiation with Ge ions) by irradiating with 100 MeV silver ions.

Liu *et al.* (2004) produced high-quality single-crystal Ge on insulator by selectively seeding Ge in windows that exposed underlying silicon in a nitride-masked silicon substrate. The 100-nm thick Ge is first sputtered over the nitride mask, and then encapsulated with a low-temperature oxide to form a self-aligned “microcrucible” to prevent agglomeration of germanium in the liquid state. The germanium is melted by a rapid thermal annealing, and the entire encapsulated Ge layer, 20 microns long, is solidified as a single crystal. This work is interesting due to the thin layer of Ge used, and that it does not require a traveling heated zone for the crystallization step.

Tsao *et al.* (2009) investigated the low-temperature growth of polycrystalline Ge thin films on glass, with post-deposition solid-phase recrystallization. Ge films were sputtered on SiN_x -coated borosilicate glass at substrate temperatures ranging from 255 to 450 °C, to a thickness of

300 nm, and then capped with 50 nm of SiO_2 . Solid-phase crystallization was performed by heating the samples in a nitrogen ambient for 20 hours at 400, 500, or 600 °C. Best crystallinity was obtained with substrate temperatures of 450 °C, without the need for a post-deposition solid-phase crystallization step. It was suggested that the high-crystalline quality obtained by these methods could be promising for thin film solar cells on glass.

More fundamental studies of Ge nucleation on SiO_2 in molecular beam epitaxy were undertaken by Leonhardt *et al.* (2009). An oxide masking layer was patterned to expose the underlying silicon substrate, which provided sites for preferential nucleation. Nucleation densities were observed as a function of substrate temperature, Ge flux, and distance from a window etched in the oxide mask to expose the underlying silicon as sites for preferential nucleation and as a sink for adsorbed Ge atoms diffusing over the surface oxide. These studies indicated the difficulty in controlling

nucleation of Ge in deposition processes that occur far from thermodynamic equilibrium, such as MBE, MOCVD, sputtering, and evaporation, and accounts for the fact that virtually all methods of achieving large-grain Ge films on dissimilar substrates have relied on a melting and regrowth, or to a lesser degree of effectiveness, solid-phase recrystallization.

A novel approach for providing large grain or even single crystal Ge as a template for epitaxial growth of GaAs is due to Flamand *et al.* (2005). A porous silicon layer is formed on a silicon substrate by electrochemical anodization methods in a bath of HF:HCH₃COOH. The porous silicon is plated with a thin 100-nm thick Ge layer by plasma-enhanced CVD. A ~6 μm -thick Ge layer is then grown by Close-Spaced Vapor Transport (CSVT) which is a simple, inexpensive epitaxial growth method using water vapor as a transport agent. The PECVD Ge interlayer proved essential in achieving (epitaxial) monocrystalline CSVT Ge layers. This approach could have the following advantages. First, the porous silicon layer may serve as soft buffer layer to accommodate stress due to lattice mismatch and thermal expansion mismatch between Si and Ge. Second, the combination of thick Ge deposit and porous silicon layer could perhaps provide a metallurgical barrier between the silicon substrate and GaAs epilayers grown on the CVST Ge. This could allow the use of metallurgical-grade silicon wafers as low-cost substrates for GaAs solar cells.

III-V SOLAR CELLS ON SILICON

Considerable effort has been directed at monolithically integrating GaAs (and other III-V materials) devices on silicon substrates. In addition to detectors, field-effect transistors, bipolar transistors, lasers, and LEDs, solar cells figure prominently in this work. After laser diodes, solar cells are probably the most sensitive of the above devices to material quality. Therefore, the performance of

III-V solar cells heteroepitaxially grown on silicon substrates is a good indicator of the viability of these methods for producing material suitable for various semiconductor device technologies. One reason for interest in GaAs-on-silicon solar cells is due to space applications. The stronger and less-dense silicon substrate affords a considerable weight reduction. Heteroepitaxy of III-V devices on silicon must address lattice-mismatch (4% for GaAs-on-silicon and 9% for InP-on-silicon), thermal expansion mismatch, formation of anti-phase domains, and interdiffusion of substrate and epilayer components. These problems have been solved to varying degrees, but still, the performance of III-V solar cells on silicon significantly lags that of III-V solar cells on better matched III-V binary substrates and Ge. Soga *et al.* (2000) achieved an efficiency of 18.3% for a fairly standard design Al_{0.8}Ga_{0.2}As heteroface *p-on-n* GaAs homjunction solar cell. Performance was improved by hydrogen plasma passivation and thermal annealing. A considerably more sophisticated (13 epitaxial layers) dual-junction GaInP/GaAs solar cell was demonstrated on a metamorphic SiGe/Si substrate which included a step-graded SiGe buffer layer as a defect filter (Lueck *et al.*, 2006). This approach reached an active area efficiency of 18.6%, with prospects for continued fine tuning and enhanced efficiency. Under high optical concentration, the effect of defects on performance will saturate. This is borne out by an earlier result reported by Vernon *et al.* (1999) showing 21.3% (at ~200 suns) for an MOCVD GaAs on silicon solar cell.

Approaches based on GaAs-on-silicon (and InP-on-silicon) are probably not a viable route to low-cost thin film solar cells unless a high-efficiency tandem solar cell can be made. While the best GaAs-on-silicon cells may approach 20% efficiency, this is roughly comparable to where commercial high-efficiency silicon solar cells can be expected to perform. Therefore, it would be difficult to justify adding epitaxial growth to a silicon wafer without achieving a more significant

improvement in efficiency. The use of a low-quality (metallurgical grade and/or polycrystalline Si) would gain some cost reductions, but probably incur too high a penalty in performance and reliability. Recrystallized silicon layers low-cost substrates might also be an option to use GaAs on silicon in an inexpensive substrate configuration. Nevertheless, the epitaxial growth technologies and methods to address lattice and thermal expansion mismatch as developed for III-Vs on silicon will be useful in other types of low-cost III-V solar cells. For example, in studies of GaAs diodes and solar cells on Si substrates with SiGe buffer layer, Andre *et al.* (2005) concluded that *p*-type emitter / *n*-type base GaAs solar cells were more tolerant of dislocations than the *n*-type emitter / *p*-type base configuration. Clark *et al.* (2006, 2005) are utilizing epitaxial BeTe and ZnBeTe buffer layers to bridge the lattice mismatch and between silicon and AlGaAs/GaAs quantum well solar cells. Sandoval *et al.* (2010) are growing GaAs films on nanostructured silicon substrates as a means of reducing defects in the GaAs. For such GaAs grown by MOCVD on nanostructured silicon substrates, improved material quality is inferred by photoluminescence characterization, and defects levels reduced to 10^3 cm^{-2} , comparable to those achieved in GaAs/GaAs homoepitaxy, are expected. (For MBE grown GaAs, 'whisker' growth is observed on the nanostructured silicon substrates.)

III-V SOLAR CELLS ON RE-USABLE SUBSTRATES

The reuse of substrates is still another venue for lowering solar cell costs. A thin, multilayer solar cell is grown on a substrate (e.g., GaAs) that seeds its epitaxial growth. The solar cell structure is bonded to a superstrate, such as glass or metal, and then separated from the substrate upon which it was seeded. The substrate can then be repeatedly re-used to produce more solar cells. Thus,

the substrate cost is spread out over many solar cells. As with GaAs-on-silicon, the advantage of this approach may be in attaining a substrate that is lighter in weight, or has more desirable electrical, optical, or mechanical properties, such as for space power applications, rather than realizing lower cost solar cells. The economics will depend on the number of times the seeding substrate can be re-used, the cost of the superstrate, the largest feasible substrate size, the yield, and the cost incurred by additional processing steps needed for separating the epitaxial layer from its substrate, attachment to the superstrate, and any reconditioning of the substrate for re-use.

One of the earliest reports of this concept (applied to silicon solar cells) was by Milnes and Feucht (1975). A silicon wafer is coated with an epitaxial SiGe layer, followed by a 20-micron thick epitaxial silicon solar cell. When heated, the SiGe alloy (lower melting point than silicon) melts and releases the silicon solar cell. The silicon wafer can then be re-used. Stirn (1980) proposed a related 'peeled-film' approach for GaAs-based solar cells, where a 4-micron thick GaAs solar cell is grown on a GaAs substrate coated with a thin, etchable AlAs layer. The AlAs release layer is selectively etched with hydrofluoric acid or redox solutions such as potassium iodide. This method of layer transfer to a surrogate substrate became more commonly referred to as *Epitaxial Lift Off*. In another early version of this approach, called CLEFT, Cleaved Epitaxial Film Transfer, (Fan *et al.* 1984; Bozler *et al.* 1984), the separation of the substrate from the epitaxial solar cell structure was facilitated by epitaxial lateral overgrowth, wherein prior to epitaxy, the substrate is masked with a dielectric film. The mask layer is patterned with stripe openings that expose the underlying substrate and acted as selective seeding regions to initiate epitaxy. During subsequent stages of growth, the crystals seeded at the stripe openings overgrow the mask and eventually impinge with growth fronts of crystals seeded at adjacent stripe openings, coalescing to form a continuous

film atop the mask. Konagai *et al.* (1978) realized 13.5% efficiency GaAs solar cells with the selectively-etched AlAs release layer approach, as an early validation of its potential, and also suggested that multilayered solar cell stacks could be used to release more than one solar cell structure from a substrate. Using the CLEFT process described above, Bozler *et al.* (1984) reported efficiencies as high as 17% on 0.5 cm² solar cells.

Zahraman *et al.* (1994) used ELO AlGaAs solar cells as top cells for a tandem AlGaAs/silicon solar cell. The transferred film approach avoids the parasitic absorption of the top cell that would diminish the bottom silicon cell performance. The measured efficiency of the Al_{0.2}Ga_{0.8}As/Si tandem reached 21% AM1.5. Lee *et al.* (1997) used ELO to demonstrate GaAs solar cells on glass substrates with total thickness of the active (light-absorbing) layers as thin as 0.32 μ m. Yazawa *et al.* (1998) used MBE (molecular beam epitaxy) and ELO to make GaAs solar cells with GaInP window layers on quartz substrates. Chang *et al.* (1999) substituted a vapor-phase etch of the AlAs release layer, in place of the liquid HF etch for selectively etching, which could improve the manufacturability of the ELO process. Omnes *et al.* (1996) demonstrated ELO GaAs solar cells on Pd-coated silicon substrates, achieving a 20% efficiency. Arokiaraj *et al.* (2000) used ELO to transfer GaAs pn junction solar cells to selenium sulphide (SeSe₂) treated silicon substrates. The SeS₂ layer can provide interface passivation.

Schermer *et al.* (2006) deposited a gold reflector layer on GaAs-based solar cells transferred to substrates by ELO, and the resulting photon confinement provided devices with efficiencies of 24.9% efficiency, comparable to similar epitaxial solar cells on GaAs substrates. Their designs included bifacial cells, reduced cell thicknesses, and processing cells grown on both sides of the seeding wafer. The performance potential of GaAs solar cells by ELO is indicated by the 26.1% efficiency reported by Bauhuis *et al.* (2009). Tseng *et al.* (2009) transferred GaAs solar

cells to gold-coated copper substrates. Solar cell performance was improved due to the enhanced light absorption effected by the Au mirror coating, and the higher open-circuit voltages from lower reverse saturation currents (through lower operating temperatures) by the heat dissipation of the copper substrate.

More sophisticated solar cell structures can be made by ELO. For example, Chao *et al.* (2009) transferred double-junction InGaP/GaAs microcuboid array onto glass, where the epitaxial structure is ‘diced’ into a rectangular array of 25- μ m x 25- μ m ‘cuboids’ before transfer, which speeds up the release etch. ELO techniques have also utilized mesoporous GaAs layers made by etching to facilitate film transfer. InGaP/GaAs/InGaAs inverted metamorphic (IMM) triple junction (TJ) solar cells were fabricated on epitaxial liftoff (ELO) GaAs wafers, 100 mm in diameter, with an efficiency of 30% at one sun, and an efficiency of 36.3% at concentration of 264suns (Rao *et al.* 2010). This is the highest reported efficiency for IMM ELO thin cells to date.

From the cost perspective, the most pressing issue is the practicality of substrate re-use. Bauhuis *et al.* (2010) used ELO to transfer GaAs-based solar cells from 4-inch diameter Ge and 2-inch diameter GaAs wafers. The wafers were re-used several times, but the wet-etch release had to be combined with chemico-mechanical polishing to render it suitable for repeated epitaxy. This substrate re-preparation removed 11 microns of substrate material, implying a substrate could ultimately be re-used ten to twenty times.

ASSEMBLED III-V MICRO SOLAR CELL SYSTEMS

Some new approaches for solar cells circumvent intractable or stubborn materials problems associated with large-scale crystal growth and thin film deposition by using micro assembly techniques. These include inkjet and contact printing, parallel

transfer, robotic pick and place, and fluidic self-assembly. These methods represent a substantial departure from the traditional solar cell paradigm of fabricating solar cell structures in intact wafers or in *as-grown* thin films on a substrate. In some sense, these methods are extensions of selective growth of solar cell arrays, epitaxial lift-off and film transfer, and Sliver[®] technologies discussed above. The new approaches are diverse and cannot be neatly categorized, but discussions of a few representative cases will provide an appreciation for their potential advantages. Generally, small solar cells are fabricated by epitaxy and micro-fabrication, separated from their substrate, and then assembled into macro arrays on a second (low-cost) substrate. The rationale being that small, high-performance solar cells can be made more easily than large-area solar cells, as large-area thin film solar cells encounter difficulties in scale-up. For instance, the etch release process in epitaxial film transfer is easier to perform on small die compared to large-area continuous films of conventional solar cells. Scale-up is achieved in post-growth assembly, and this approach is recently enabled by advances in microfabrication, printing, and fluidic technologies that offer cost effective means for assembly. We include a review of reports where these methods were demonstrated with silicon solar cells or with LEDs and other devices, because it appears feasible to apply similar methods to III-V solar cells.

A University of Illinois (Urbana-Champaign) research group has developed transfer printing techniques to create flexible arrays of solar cells, III-V LEDs and microelectronic devices. Yoon *et al.* (2008) made arrays of silicon solar cells as narrow strips of silicon (length = 1.5 mm, width = 50 μm , thickness = 15 μm) released by undercut etching from a silicon wafer onto a soft elastomeric stamp, and subsequently transferred by contact printing on a flexible polymer substrate. Electrical interconnection was made by evaporating metal onto the polymer substrate through a shadow mask. A lenticular lens array placed over

the solar cell array reduces photocurrent losses due to gaps between cells and grid shading. Park *et al.* (2010) used *etch and release* processes to form microscale (100 x 100 micron up to 500 x 500 micron) AlGaAs LEDs. Transfer printing lift these devices from the seeding wafer and deliver them into sparse arrays on polyethylene terephthalate sheet. The sheet is coated with thin layers of photocurable polymers that define interconnection metallization patterns. These methods have also been used to make printed arrays of transistors, diodes, and circuits on plastic substrates (Sun *et al.* 2006; Kim *et al.* 2008). Yoon *et al.* extended the productivity of this technique by growing releasable multilayer assemblies of the GaAs solar cells. They demonstrated 10 x 10 interconnected arrays of (500 x 500 micron) GaAs solar cells.

Fluidic self-assembly has been developed as a means to site small solar cells on a host substrate. For example, batches of small mesa solar cells can be made by selective growth and released by undercut etching, or diced from a substrate. The solar cells, suspended in a liquid, are then flowed over the substrate where they will eventually settle into recesses formed in the substrate. In this scheme, the substrate for epitaxy could be re-used. Figure 10 below shows a process developed by Soga *et al.* (2003) for fluidic assembly of thin, disk-shaped (50-micron diameter) GaAs on oxide-coated silicon substrates. The solar cell 'blocks' are released from the GaAs seed substrate by wet etching and suspended in methanol which serves as the carrier fluid. As the liquid mixture of methanol and GaAs blocks flows over the silicon substrate (with recesses formed in the oxide coating), virtually all the recesses are eventually filled with GaAs blocks. Stauth and Parvitz (2005) demonstrated integration of silicon components on plastic substrates using fluidic self-assembly. Silicon devices are released from a substrate and suspended in an aqueous solution. The complementary shape between the substrate wells and silicon chips provides for a shape recognition effect such that different devices can be selectively

sited on the substrate. Self-assembly is due to the gravitational forces in that devices fall into the wells, and capillary forces of molten solder bind the device to the substrate and provide electrical connection.

A University of Minnesota group has published extensively on various applications of assembly arrays of microscopic devices made by fluidic surface-tension directed self-assembly (Chung *et al.* 2006; Kneusel and Jacobs 2010). Figure 11 shows a process for surface tension-directed self-assembly at a liquid-solid interface. The various interface energies in water vs. silicon oil as a solvent provide the driving forces for transfer and placement of die on the substrate, such that the die ($20 \times 60 \mu\text{m}$) are sited on liquid solder contact pads. For silicon solar cell arrays, there is an approximate factor of 10 reduction in silicon usage, due to the 20-micron thickness of the chips (compared to several hundred microns for a wafer) and the factor of 4 reduction in silicon area coverage, which would be compensated by cover slip optics placed over the array. Zheng and Jacobs (2005), and Kneusel and Jacobs (2009) extended these techniques for directed three-dimensional self-assembly, perhaps of use for tandem or multijunction cell applications of non-lattice-matched semiconductor systems.

A Sandia National Laboratories group (Gupta *et al.* 2010) has described a Microsystems-enabled technology for making solar cell arrays for silicon and III-V solar cells intended for concentrator applications. GaAs cells are grown on a handle wafer and processed into hexagonal-shaped solar cells (20 microns total thickness, 250 microns to 1 mm in lateral dimension), released from the wafer, suspended in a liquid carrier, and deposited on receptive sites formed in an interconnection layer, and encapsulated in a flexible substrate with a microlens array that concentrates sunlight onto the cells. This fluidic assembly approach would reduce array costs in several ways: making cells with small dimensions (reducing material consumption and facilitating layer transfer), and

using micro-concentrators to replace active solar cell area with cheap plastic optics. Flexible substrates would allow deployment of arrays on the contours of natural terrain and buildings, as well as in portable electronics and on vehicles. To date, 3-micron thick GaAs cells used in this process have 10% efficiency, while 14-micron silicon solar cells have 14.9% efficiency. Much higher efficiencies with more sophisticated 3-5 cell structures appear feasible.

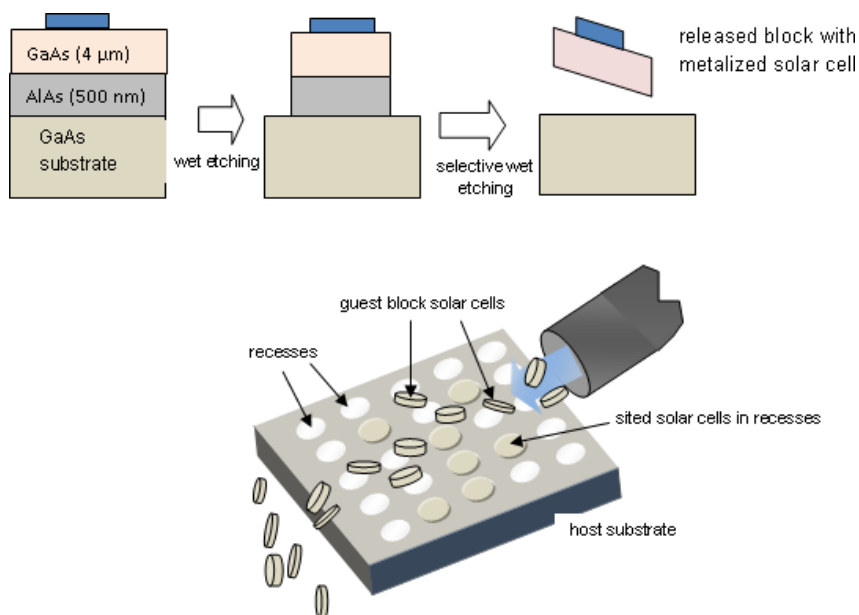
Semprius (Durham, NC) is developing photovoltaic modules using micro-transfer printing and surface mount technology (Furman *et al.* 2010). The cells are dual-junction GaInP/GaAs cells ($< 5 \text{ mm}^2$ in area) made by an ELO process. Figure 12 shows steps of the microtransfer printing process. Module efficiencies greater than 25% have been achieved.

Another application of self-assembly for solar cells is the formation of a coating of 1-micron monodisperse polystyrene microspheres on the surface of the solar cell which boosts light absorption and current generation by 25% (relative increase) [Chang *et al.* 2009], as shown in Figure 13.

CONCLUSION

Solar cells based on III-V semiconductors represent the state-of-the-art for performance, but they are too expensive for large-scale power generation. This stems primarily from the high cost of the single-crystal substrate wafer and secondarily from the epitaxy and device fabrication. On the other hand, polycrystalline III-V thin-film solar cells on dissimilar substrates such as metal or glass, similar to other compound semiconductor solar cells such as those based on CdTe or copper indium diselenide, could provide a low-cost route for photovoltaic solar energy. Points in favor of this approach include: 1) the demonstrated high efficiencies (30-40%) of tandem GaAs-based solar cells, 2) the respectable efficiencies (20%)

Figure 10. Fluidic self-assembly of GaAs devices using epitaxial lift off (top) and deposition from a flowing suspension over a receptor host substrate (bottom); (After Soga et al., 2003).

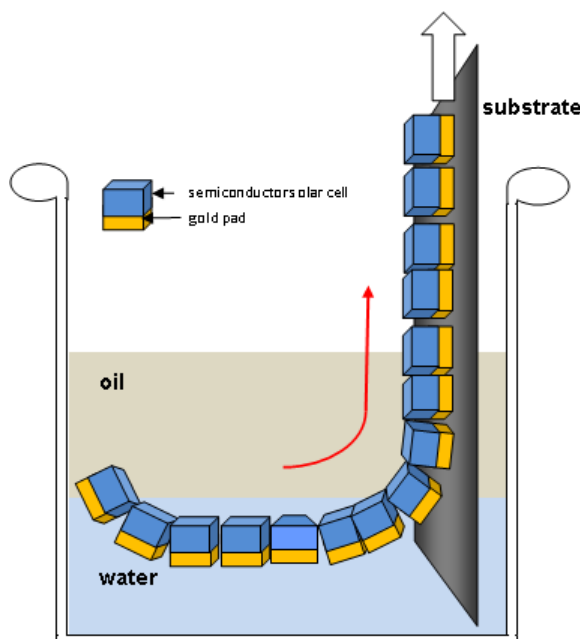


of single-junction GaAs solar cells grown on large-grain Ge wafers, and 3) the highly developed technology base of III-V semiconductors (compared to other non-silicon semiconductors), due to their use in optoelectronics. Against this approach is the lack of substantial progress or commercialization of a low-cost thin-film III-V solar cell despite considerable effort. Work on low-cost III-V solar cells dates from the 1970s, although with substantially less effort than that expended on amorphous silicon, CdS, CdTe, and CuInSe₂ solar cells. To date, there is a considerable gap between the performance of epitaxial III-V solar cells grown on single-crystal wafers, and solar cells made in thin polycrystalline III-V films deposited directly on low-cost substrates. A combination of small grain size and grain boundary electrical activity reduces the efficiency by roughly 30-50% compared to commercial single-crystal GaAs solar cells. Based on the work reviewed in this chapter, there does not seem to be any immediate prospects for improving material quality of GaAs thin films deposited directly on the obvious choices

for substrates such as glass, graphite, ceramics, and metal sheets. However, a recent development describing growth of GaAs on oxide (MgO)-coated hastalloys, as reviewed above, suggests perhaps innovative substrates might be the key to making direct epitaxy work, rather than new methods of epitaxy. The GaAs-on-silicon, as well as other III-V semiconductors growth heteroepitaxially on silicon, does not appear to be a promising avenue for significant cost reductions.

On the other hand, the growth of GaAs-based solar cells on large-grain Ge has demonstrated considerable potential. While Ge wafers are as costly as III-V wafers, thin Ge layers can be readily deposited and recrystallized on a variety of low-cost substrates such as alumina. In fact, as most high-efficiency GaAs-based tandem cells utilize a bottom Ge cell, the incorporation of a Ge interlayer between the substrate and GaAs layers could be viewed as an advantage. Because Ge is relatively expensive, the thickness of the Ge interlayer must be kept thin, on the order of a micron or less. The crucial elements constituting

Figure 11. Self-directed fluidic assembly of solar cell array from suspension of small solar cells. Solar cell assembly on substrate schematised as substrate is withdrawn from a beaker containing two immiscible layers of oil and water; After Chung et al. (2006); Kneusel and Jacobs (2010)

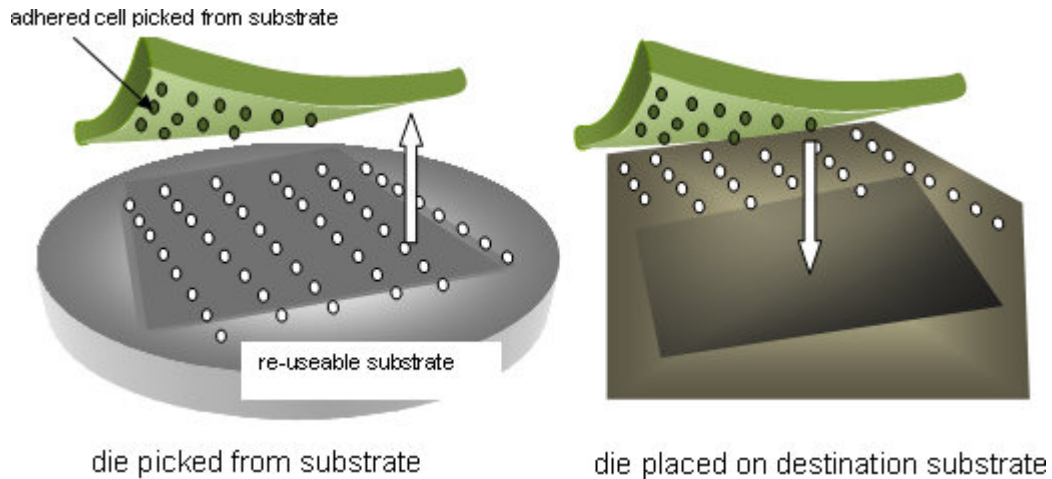


a proof of concept for this approach have been demonstrated, in that epitaxial growth of a GaAs solar cell on a recrystallized Ge buffer layer formed on a low-cost, e.g., ceramic, substrate is feasible. Yet this type of thin-film GaAs solar cells, similar in concept and design to traditional thin-film solar cell technologies, has not been pursued to any great extent in the last ten years.

Solar cell approaches based on GaAs (and other III-V semiconductors) on silicon appear to have little potential for dramatic cost reductions. The epitaxial layer transfer or epitaxial lift off (ELO) techniques may be more promising in this regard, but manufacturing cost is still a concern. This technology nominally reduces the high cost of using a GaAs wafer but the viability of these processes for commercial solar cell production, when applied to large-area, and particularly with respect to yield and scale-up, remains in question. More generally, these approaches validate various design concepts for a thin GaAs solar cell on a dissimilar substrate.

There have been numerous reports of microassembly methods for producing arrays of small solar cells on flexible substrates. These include fluidic assembly, transfer printing and other methods reviewed above. These approaches represent a considerable departure from previous and current solar cell technology by circumventing the need for scaling up the throughput and area of materials processing steps such as crystallization and epitaxy, thin-film deposition, metallization, and surface treatments. Whether such methods will achieve the yields and low-costs needed for terrestrial solar cell production is difficult to gauge at this early stage. As these techniques have wider applications to LEDs and other ‘macroelectronic’ uses, continued development and commercialization efforts can be expected. It is worth mentioning that solar cell arrays made by microassembly processes can utilize small die (less than 1 mm). Smaller dimension die facilitates etch release and film transfer in epitaxial lift-off processes. The use of self-assembly methods to make GaAs

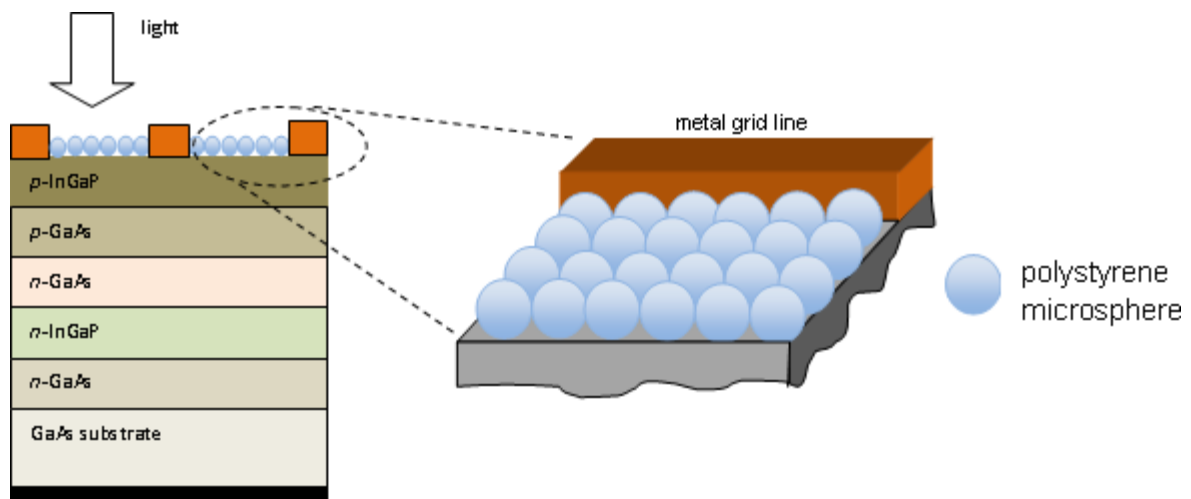
Figure 12. Semprius microtransfer contact printing process for solar cells on flexible substrates (After http://www.semprius.com/tech_micro-transfer.htm)



solar cell arrays on flexible plastic substrates, including sparse arrays that would reduce material consumption of precious semiconductor, but which could be compensated by plastic microlens concentrators formed over the array, may hold forth the best prospects for III-V solar cells as low-cost solar electric systems. Further developments in low-cost, high-throughput epitaxy of III-V compounds to grow the solar cell die would also

boost the prospects of this approach. The stability of III-V semiconductors, as proven by their long-term use in optoelectronics and satellite solar power, and their suitability for exploiting effects needed in 'third-generation' photovoltaic designs give further impetus to a low-cost III-V solar cell.

Figure 13. Use of microsphere coatings to improve reflection and optical enhancement of GaAs-based solar cells (After Chang et al., 2009)



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Chapter 11

Materials Characterization Techniques for Solar Cell Devices: Imaging, Compositional and Structural Analysis

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ABSTRACT

Characterization of an issue provides the required information to determine the root cause of a problem and direct the researcher towards the appropriate solution. Through the explosion of nanotechnology in the past few years, the use of sophisticated analytical equipment has become mandatory. There is no one analytical technique that can provide all the answers a researcher is looking for. Therefore, a large number of very different instruments exist, and knowing which one is best to employ for a specific problem is key to success.

INTRODUCTION

A large number of analytical techniques have been developed to determine the properties of a specimen. The reason behind this variety is that each method will provide a very specific type of data. Therefore, in order to fully characterize a specimen, a variety of such methods need to be implemented. Most of these techniques rely on

the same principle: an incident beam of photons or charged particles interacts with the specimen generating various types of signals. Part of these signals is collected by an appropriate detection system and the data is analyzed to provide information on the properties in question (Brandon and Kaplan 1999).

The purpose of this chapter is to give a short description of the most widely used analytical

techniques along with their advantages and disadvantages. The end goal is that the reader will be able to determine which technique is most suitable for a given situation.

BACKGROUND

Analytical instruments and analysts can be seen as “problem solvers.” In almost any environment the solution requires the knowledge of all processing steps underwent by the specimen. The more information available the more likely it is an answer will be found. Often enough analytical results can be interpreted in more than one way due to various issues, such as overlaps, detection limits and resolution. A separate piece of information, obtained by other means, can rule out one scenario and support another. Furthermore, an absolute answer may sometimes not be obtainable due to various limitations. In such cases a comparative analysis is performed between a “good” and a “bad” sample. A “good” sample is a reference, a structure that “works,” or a thin film that does not show the problem. Differences in the collected signals can point to the correct direction without necessarily knowing the absolute values of the measured quantity. This approach is known as qualitative analysis. When a traceable standard is used, for example a structure with known dimensions or a film with a known composition, then the instrument can be calibrated based on this standard and quantitative results are obtained.

IMAGING

Everyone has heard of the expression “a picture is worth a thousand words.” When we are presented with a sample that does not “work,” our first reaction is to examine it and see if there is something obviously wrong with it. The following section will cover the most commonly used techniques that are used to examine a specimen.

Optical Microscopy

Optical microscopy is the first line of defense. It is often the first technique used to assess the condition of a sample and such instruments are found in almost every laboratory. Optical microscopy is used to examine surfaces for imperfections, contaminants, micro-cracks or to make ourselves familiar with the sample and make markings that can be used later in a different technique to more easily navigate to the region of interest. Variations of brightfield microscopy are also used to extract information that may not be otherwise visible (e.g. darkfield, uv fluorescence and polarized light microscopy).

Little or no sample preparation is required and optical inspection of interior features is possible through optically transparent layers. Using calibrated magnification standards, feature sizes down to a few micrometers can be seen and measured (the magnification limit is of the order of 2000x in air).

Scanning Electron Microscopy

Scanning Electron Microscopes (SEM) use a finely focused beam of electrons that is scanned over the surface of the specimen. The incident electrons undergo a series of elastic and inelastic collisions creating various signals, including secondary and backscattered electrons. These signals are used to form an image of the specimen on the viewing monitor (Goldstein 1992).

The basic components of an SEM are the electron gun, the lens system, the electron detector, the vacuum system and the viewing monitor. An electron source is incorporated in the gun assembly and provides electrons by thermionic or more typically these days field emission. The emitted electrons are accelerated to energies, usually, up to 40keV and are focused by the lens system to a spot of the order of 1nm. A deflection system scans the electron beam along a line which is then displaced for the next scan until a rectangular

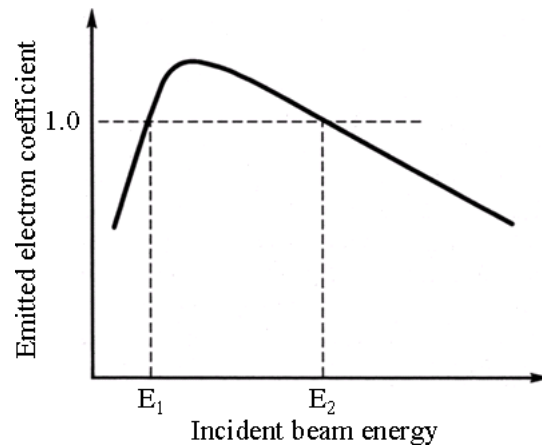
raster is generated that covers the inspected area on the specimen. There is a point-to-point correlation between the location on the sample where the electron beam strikes and the location on the viewing monitor where the image is formed. The signal from each point is collected and is used to modulate the intensity of the corresponding point on the viewing monitor thus creating an image. The magnification of the image is the ratio of the linear size of the viewing monitor to the length of the line that is scanned on the specimen. Therefore, higher magnifications are obtained by simply scanning the electron beam over smaller areas. A wide range of magnifications are available, from about 10x to over 500,000x with a resolving power of the order of one nanometer. Due to this, SEMs are widely used these days and there are few laboratories in the world, if any, without one in their arsenal.

Forming an image using the secondary electron signal will provide topographic information and an image formed by backscattered electrons will provide images with atomic number contrast (elements with higher atomic number have higher backscatter electron yields).

The mean free path of electrons is very small in air, therefore the electron column and specimen chamber are kept under vacuum. Therefore, specimens need to be vacuum compatible. Furthermore, the specimen needs to be fairly conductive in order to avoid charging effects. However, since incident electrons enter the sample and secondary and backscatter electrons escape the sample, non conductive samples can be imaged if the ratio of incoming to outgoing electrons is close to unity. The total emitted electron coefficient varies as a function of incident beam energy as shown in Figure 1. Therefore, operating between the two crossover energies, E_1 and E_2 , can allow us to image challenging samples.

In addition to modifying the incident electron beam energy, environmental SEMs have been developed where an imaging gas is present in the vacuum chamber (operating at higher pressures

Figure 1. Total emitted electron coefficient as a function of incident beam energy. Typical E_2 values for quartz, Teflon, and PVC are 3.0, 1.82, and 1.65keV, respectively.



compared to conventional SEMs) allowing the imaging of a larger variety of samples.

Minimal sample preparation is required before a sample can be introduced in the SEM chamber. A sample may be coated with a thin conductive layer to reduce charging effects or material delineation through light etching may be also implemented for decoration purposes to enhance contrast.

In addition to the secondary and backscatter electrons, Auger electrons, characteristic and Bremsstrahlung X-rays are created amongst other signals when the incident beam of electrons interacts with the specimen. Combined with an X-ray detector, an SEM can provide compositional analysis and with the use of an electron backscatter diffraction detector, information on crystallographic orientation can be obtained making an SEM an extremely useful and versatile tool to have available in any laboratory (Reimer 1998).

Focused Ion Beam Microscopy

Focused Ion Beam (FIB) instruments use a finely focused beam of Gallium ions that is scanned over the surface of the specimen. The principles of operation are very similar to that of an SEM

with the only difference that Ga^+ ions are used instead of electrons and hence a modified lens system is also required.

Due to the nature of Ga^+ ions, upon impinging the specimen surface not only they generate various signals, including secondary electrons used for imaging, but they also very lightly sputter material away. This can be used to remove material locally without affecting the surrounding region. Furthermore, FIBs are typically equipped with a gas injection system that can be used to either remove material from selected regions at higher rates, as opposed to just using the ion beam, or deposit materials by using different chemistries. For example, a region of a specimen can be protected by depositing a thin film of platinum or tungsten and sputter away material from the surrounding area in a manner that the protected area can now be inspected in cross-section to measure film thickness or examine subsurface features.

The above unique capabilities make FIBs increasingly popular and are now equipped with an electron column in addition to the ion column for added flexibility. These instruments are widely used in failure analysis (Hatzistergos 2004) and are critical in preparing specimens that are to be analyzed in other techniques such as transmission electron microscopy and atom probe tomography that will be discussed later.

Transmission Electron Microscopy

Transmission Electron Microscopes (TEM) use a finely focused beam of energetic electrons that pass through a thin specimen. The transmitted electrons are collected to form images with atomic resolution.

Being an electron microscope, TEM requires the use of vacuum but the most characteristic aspect is the specimen characteristics. Specimens that are analyzed in a TEM typically have the form of a lamella which thickness is usually 50-200nm. Solids are not transparent to electrons, hence the thin lamellas. In addition, the incident beam of

electrons is accelerated to high energies, in general 100-400keV in order to ensure that electrons can easily pass through the specimen and to be able to achieve small spot sizes. Post specimen lenses collect the transmitted electrons to form an image. The smallest distance that can be resolved is related to the wavelength of the imaging beam. For electrons:

$$\lambda = 1.22E^{-1/2} \quad (1)$$

where λ is the electron wavelength in nanometers and E is the energy of the electron in electron volts. Therefore, for 100keV electrons, $\lambda \sim 4\text{pm}$, which is enough to provide images with atomic resolution. Furthermore, electron scattering patterns (diffraction patterns) can be recorded and used to identify material phases.

Sample preparation is critical and labor intensive. Specimens can be thinned to the required thickness by traditional polishing methods or more recently by using a FIB. Images with magnifications of several millions can be achieved; hence material differences can be distinguished on the nanometer scale. However, one has to be careful of how representative TEM analysis is. It is an excellent technique to analyze specific regions of a specimen but it does have a narrow field of view (Reimer 1993, Williams and Carter 2009).

Combined with an X-ray detector or an electron energy loss detector, a TEM can also provide some compositional information.

Scanning Probe Microscopy

In Scanning Probe Microscopy (SPM) a sharp probe is positioned in close proximity to a specimen surface and is then scanned over the sample. The probe-sample interaction is measured and the resulting information is used to construct a map. The measured properties may include lateral frictional forces, surface potentials, electrostatic, magnetic, capacitive, or resistive interactions between the tip and the specimen surface. One

of the most commonly used SPM derivatives is Atomic Force Microscopy (AFM) which is used to characterize surface morphology with atomic resolution. The AFM setup shown in Figure 2 forms the base platform for many SPM techniques.

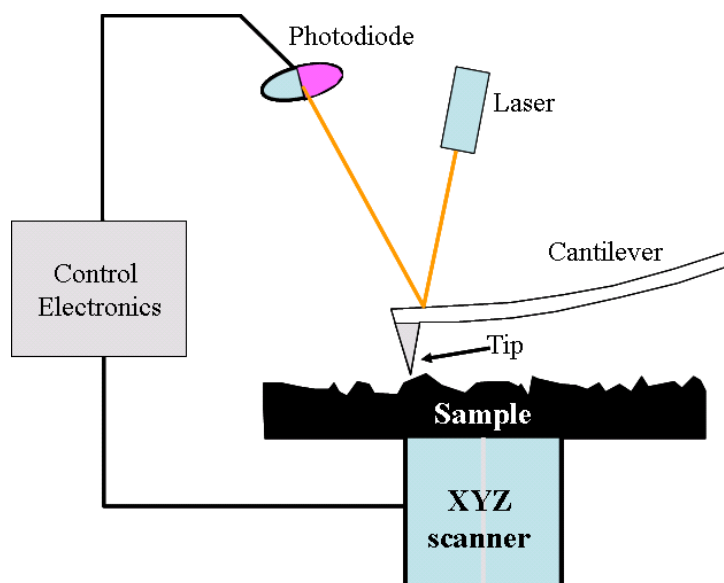
There are many variations of AFM measuring topographic, electrical and phase differences, but the basic principle is the same for all. A sharp tip, with a radius of curvature of the order of a few nanometers, is part of the free end of a cantilever. The tip-cantilever system is usually made of silicon or silicon nitride and is brought in contact or in close proximity to the specimen surface. AFMs rely on the forces, e.g., van der Waals, between the tip and the specimen surface. These forces are calculated by measuring the deflection of the cantilever which is typically measured by reflecting a laser spot from the backside of the cantilever into a position sensitive detector.

There are several operating modes for AFM with different capabilities. Depending on the sample and the type of information that is sought the appropriate mode is used. In contact mode a low spring constant cantilever (typically 0.1 N/m)

is used as the tip is scanned in continuous contact with the surface. In non-contact and tapping modes a high spring constant cantilever (typically 1 to 100 N/m) is used as the cantilever is oscillated at frequency slightly over its resonant frequency. In non-contact mode the amplitude of the cantilever oscillation is under 10 nm where van der Waals forces and/or other long range forces tend to decrease the resonance frequency of the cantilever. Therefore, a topographic image can be constructed by adjusting the distance between the tip and sample in order to maintain a constant amplitude or frequency as the tip travels over the various surface features. In tapping mode the oscillation amplitude is of the order of 100 nm and the net force between long and short range forces is used to image the surface (Wiesendanger 1998).

AFM is a non-destructive technique that is typically used to measure surface roughness, step heights, and film properties such as hardness and Young's modulus. When equipped with the appropriate hardware and operated in the corresponding mode it can also provide electrical measurements. For example, Scanning Capacitance Microscopy

Figure 2. AFM setup consists of a probe (cantilever and tip), a laser beam system, control electronics, and a xyz scanner



(SCM) and Scanning Spreading Resistance Microscopy (SSRM) are used to measure local carrier concentrations in a doped semiconductor.

No sample preparation is required to collect topographic information; however, when used in modes such as SCM and SSRM, specimen preparation can be very labor intensive.

COMPOSITIONAL ANALYSIS

The composition of a thin film or structure can explain its behavior. In both developing and manufacturing environments, recipes are built for each processing step to consistently produce films with the desired composition. When this composition falls out of an acceptable range, it affects the device performance. In qualitative analysis the main question that is answered is: what elements are present in the specimen? The additional information that is provided in quantitative analysis is the percentage of each element that is present in the specimen. The next section will cover the most commonly used techniques that provide qualitative and quantitative information.

X-Ray Fluorescence

In X-Ray Fluorescence (XRF), a beam of energetic X-rays is directed towards the specimen surface. The incident X-rays need to have enough energy to eject a core shell electron of a constituent atom. Once the atom is ionized it is in an unstable/excited state and will “relax” by having an outer shell electron fill the gap that was created in one of the inner shells. As a consequence, an Auger electron or a characteristic X-ray is emitted to balance the energy difference between the outer and inner shell (when an electron drops from an outer shell to an inner one, its energy needs to be adjusted since it can not exist in a state having the energy of another). In XRF the emitted characteristic X-rays are collected and both qualitative and quantitative information can be extracted.

Depending on which core and outer shells are involved in this electron/energy exchange, the emitted X-ray has a well known characteristic energy. By measuring the energy of the emitted X-rays one can determine what elements are present in the specimen. Furthermore, from the intensity of the collected X-rays, and using the appropriate reference material one can be quantitative with sensitivity in the high part per billion (ppb) range.

The incident X-rays, unlike electrons, can travel in and escape from great depths (micrometers). Therefore, information from subsurface regions is also collected allowing the analysis of multilayered structures. The lateral resolution of XRF ranges from several micrometers up to a few millimeters limiting its application space to large structures. However, it requires little on or sample preparation, it is non destructive and in addition to solids it can handle a large type of specimens such as powders, liquids and gels.

X-Ray Photoelectron Spectroscopy

In X-Ray Photoelectron Spectroscopy (XPS) the specimen is irradiated with a beam of X-rays. The principles behind XPS are different than those of XRF. The incident X-ray is absorbed by an electron which can escape from the specimen. By measuring the kinetic energy of the emitted photoelectron, one can calculate its binding energy and determine the identity of the atom it used to be bound to (Briggs and Grant 2003).

$$E_{\text{binding}} = E_{\text{photon}} - (E_{\text{kinetic}} - \square) \quad (2)$$

where E_{binding} is the calculated binding energy, E_{photon} is the energy of the incident X-ray photons, E_{kinetic} is the kinetic energy of the collected photoelectrons and $\square$ is the work function of the detector.

Due to the nature of the collected signal, photoelectrons, the XPS analysis requires ultra high vacuum conditions. Similarly to XRF, the incident X-rays penetrate several micrometers into the specimen, however, since electrons have a much

shorter mean free path in solids, only photoelectrons that were created usually within the top ten nanometers can escape into vacuum. Because of this, XPS is extremely surface sensitive and if subsurface regions need to be analyzed an ion gun needs to be used (XPS systems are typically equipped with one) to sputter away the top layers and expose underlying features.

The lateral resolution of XPS is similar to that of XRF, several micrometers, and requires no sample preparation but is sensitive only down to parts per thousand. However, due to its sensitivity it is capable in providing bonding information and combined with angular resolved analysis, i.e. collecting photoelectrons at different take-off angles; it can provide powerful and extremely sensitive non destructive analysis.

Analytical techniques that implement X-rays as their irradiation beam have many advantages but one of their main disadvantage is their lateral resolution. When small features (submicron) need to be analyzed then an electron beam based technique needs to be used due to the ability of focusing electrons to extremely fine spots. The most commonly used techniques that fall under this category are: electron probe microanalysis and Auger electron spectroscopy and will be described next. In addition to those two techniques when TEM is combined with an electron energy loss detector or an X-ray detector it can also provide some compositional information.

Electron Probe Microanalysis

In Electron Probe Microanalysis (EPMA) a focused beam of electrons is directed to the surface of a specimen. Figure 3 summarizes the various signals that are generated as a result of the electron-solid interactions. These signals are: heat, characteristic and Bremsstrahlung X-rays, Auger, backscattered and secondary electrons. The electron probe microanalyzer is related to SEM but it is designed to detect and measure

characteristic X-rays unlike the SEM which is used mainly for imaging purposes.

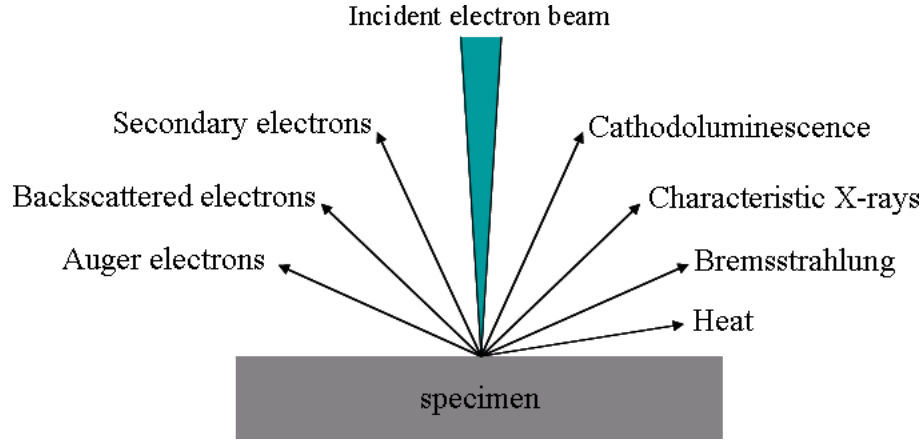
Like any other electron beam instrument, EPMA requires a vacuum chamber. Little or no sample preparation is required to perform the analysis, i.e. when a sample is not conductive; a thin coating is deposited to “drain” any surface charge buildup. There are two types of X-ray detectors that an EPMA is typically equipped with, Energy Dispersive Spectrometers (EDS), (usually found on SEMs as well) and Wavelength Dispersive Spectrometers (WDS).

EDS detectors collect the entire X-ray spectrum, i.e., any X-ray that is emitted from the specimen towards the detector can be detected. In a few seconds enough counts are collected to be able to detect the main constituents. Longer collection times are required in order to improve the signal to noise ratio for atoms that are present in lower concentrations. The energy resolution of an EDS detector is of the order of 130eV, so overlap issues exist when two or more elements that are present in the specimen have characteristic X-rays that differ less than 130eV in energy.

WDS detectors do not collect the entire X-ray spectrum that is emitted from the specimen. Instead, they need to be “tuned” to a specific energy. This could be seen as a limitation, however once a qualitative analysis is done and the present elements are known; WDS detectors are advantageous over EDS detectors. The energy resolution of a WDS detector is of the order of 10 eV, therefore overlap issues are more rare and can handle much higher count rates than EDS detectors. Furthermore, they exhibit lower backgrounds and therefore the signal to noise ratio along with detection limits are improved.

EPMA relies on standards for accurate quantitative analysis. Several “standardless” methods exist but errors as high as 150% associated with those types of measurements have been reported (Newbury 1995). When standards are used then accuracies of fraction of a percent are achievable.

Figure 3. Signals produced by the electron bombardment of a material. The incident electrons need to have enough energy to ionize the specimen atoms and emit characteristic X-rays and Auger electrons.



The standard used, can be of the form of a pure element. For example, if a NiAl alloy is to be analyzed then a pure Ni and a pure Al standard can be used, or a compound containing several elements of known concentration can also be used. This is particularly useful since it may be hard to find various elements in a pure form or stable solid state (Hatzistergos 2006).

X-rays are collected from both the unknown material and the standards under identical conditions (i.e., the same beam energy, current, take-off angle and detector position). If the alloy in question contains two elements, A and B, a ratio is formed of the background and detector dead time corrected X-ray intensity for each element over the corresponding standard, known as the k-ratio:

$$k_A = I_{\text{unknown-A}} / I_{\text{std-A}} \text{ and } k_B = I_{\text{unknown-B}} / I_{\text{std-B}} \quad (3)$$

where k_A is the k-ratio for element A and $I_{\text{unknown-A}}$, $I_{\text{std-A}}$ are the background and dead time corrected characteristic X-ray intensities for element A collected under identical conditions from the sample and from the pure element A respectively (same for element B).

To a first approximation the alloy concentration in element A is equal to its k-ratio. However, due

to three effects, atomic number (Z), absorption (A) and fluorescence (F), corrections need to be made in order to get an accurate result. Therefore, the concentration C_A and C_B for element A and B are given by:

$$k_A = C_A (ZAF)_A \text{ and } k_B = C_B (ZAF)_B \quad (4)$$

Instead of the ZAF correction in Equation 4 another method known as $\rho(\rho z)$ can be used in its place which is a different approach in applying the same corrections (Goldstein 1992, Reed 1997 and Scott 1995).

Contrary to XRF and XPS, EPMA can analyze micron sized features due to the use of an electron beam. Even though the electron beam can be focused to a spot size of just a few nanometers, the excitation/interaction volume can be of the order of a micrometer or more, depending in the energy of the incident beam and the material. Therefore, care needs to be taken when quantitative analysis of submicron features is required. Furthermore, a planar surface is essential for this kind of analysis to avoid any masking or edge effects which constricts the quantitative application space but it is still very valuable for qualitative analysis of submicron features (Gauvin 1995).

Auger Electron Spectroscopy

In Auger Electron Spectroscopy (AES) a focused beam of electrons is used to excite atoms at the surface of a specimen. Upon relaxation, X-rays and Auger electrons are emitted. By measuring the kinetic energy of the emitted Auger electrons the composition of surface layers can be determined (Briggs and Grant 2003).

The kinetic energy of the emitted Auger electrons serves as a signature to the identity of the excited atoms. By measuring the intensity of the collected signal and using sensitivity factors, determined from standards, one can determine the composition of the surface. Auger electrons are generated at various depths as the primary electron travels in the specimen. However, only those generated within ~10nm from the surface can escape and get detected. Therefore, similarly to XPS, AES is very surface sensitive and combined with an ion sputtering tool one can obtain a compositional depth profile. Contrary to XPS, AES can easily analyze sub-micrometer features and is typically used to characterize particles and defects that are as small as tens of nanometers in size. A fraction of a percent is typically the detection limit of AES.

High vacuum is required for this kind of measurements; therefore only vacuum compatible specimens can be analyzed. Since an electron beam is used, mainly metallic, semiconducting materials and thin oxides can be examined. Typically no sample preparation is required but in the event where a thick oxide needs to be analyzed, then coating the surface with a thin conductive layer may be the solution in collecting useful information.

AES spectra can suffer from overlaps as well and the analyst needs to be aware of such limitations and use the appropriate technique. For example, Ti and N overlap in an AES spectrum making it extremely difficult to extract any useful information but the Ti and N photoelectron peaks in XPS do not. Contrary, Ta and N overlap in XPS but not in AES.

Electron Energy Loss Spectroscopy

In Electron Energy Loss Spectroscopy (EELS) the energy distribution of the electrons that have gone through the TEM lamella is analyzed. These electrons can still have their initial energy or may have suffered inelastic collisions, therefore having less energy than upon entering the lamella.

The energy loss events from the interaction of the primary electron beam and the specimen can reveal a lot of information, including elemental identification, bonding information, free electron density, specimen thickness and band gap if there is one. The energy resolution is of the order of <1eV and combined with the nanometer lateral resolution, makes it a very powerful technique. However, there are some limitations with EELS. Sample preparation is very labor intensive and the lamella needs to be less than 100nm thick, less than 50nm for best results. It is highly sensitive for light elements but is lacking in heavier atoms and is difficult to quantify the results since the peak intensities in the spectrum depend on the lamella thickness (Williams and Carter 2009).

The combined TEM/EDS/EELS system is very powerful but also very expensive instrument to have. EELS and EDS are complementary techniques and most TEMs are typically equipped with both spectrometers.

Secondary Ion Mass Spectrometry

In Secondary Ion Mass Spectrometry (SIMS) the surface of a specimen is sputtered by a focused ion beam (typically oxygen or cesium). This causes the ejection of secondary ions and neutrals. The secondary ions coming off the specimen are measured by a mass spectrometer, revealing the composition of the sample.

SIMS is a destructive analytical technique. An area of 150x150 μm^2 is typically sputtered to collect enough ions and determine composition. The high number of ions coming off the specimen makes SIMS one of the most sensitive analytical techniques with a detection limit down to the parts

per billion range. Sputtering of the sample allows the study of elemental distribution as a function of depth. Therefore, layered specimens can also be analyzed with a depth resolution of the order of a nanometer. The excellent mass resolution, sensitivity and precision of these instruments make them ideal for trace element analysis (Feldman 1986 and Ronsheim 2008). Contrary to techniques relying on X-ray detection for compositional analysis, all elements can be analyzed and little or no sample preparation is required.

Smaller areas can be analyzed but sensitivity is compromised making lateral resolution an issue for SIMS. Furthermore, standards are required and because secondary ion yields are matrix dependant, standards for each material are necessary, unlike EPMA where pure elemental or compound standards are used for any matrix.

A variation of SIMS is the Time of Flight SIMS (TOFSIMS) where the time of flight of the ejected ions is used to determine the mass to charge ratio of the collected species.

Atom Probe Tomography

In Atom Probe Tomography (APT) the sample is evaporated one atom at a time and a time of flight spectrometer is used for elemental identification. A position sensitive detector allows the analyst to reconstruct the analyzed volume atom by atom in three dimensions making APT one of the few techniques that can provide 3D characterization.

APT is a destructive analytical technique, where the specimen is prepared either by electropolishing, for metals, or in a FIB in such a way that a sharp tip is formed (radius of the order of 50nm), with the region of interest carefully placed at the apex of the tip. A voltage is applied to the specimen such that the resulting field is strong enough to extract specimen atoms (typical values are of the order of a few V/nm).

In order to achieve controlled atom evaporation, a standing voltage is applied to the point where the resulting field is almost enough to cause evaporation. A short voltage pulse increases the

field strength momentarily causing an atom to evaporate. The moment the voltage pulse is applied, is marked as t_0 and the moment the evaporated atom strikes the position sensitive detector is marked as t_1 . The time difference $\Delta t = t_1 - t_0$ defines the time of flight and is essential to determine the identity of the collected atom.

The use of a voltage pulse can be applied on metallic specimens but for semiconducting or insulating samples it is replaced by a laser pulse. The implementation of a laser pulse has opened an entirely new application space; therefore, more and more APTs are now found in laboratories around the world.

APT is a unique technique providing three dimensional analysis with atomic resolution and sensitivity in the order of parts per million without the need of standards. It is ideal in analyzing grain boundaries, interfaces and structures that require both high spatial resolution and sensitivity. When used in combination with TEM and SIMS, APT can provide solutions to problems that neither could answer on their own. After data collection, the analysis volume is reconstructed in 3D allowing the analyst to extract information such as concentration profiles at any direction, 2D elemental maps and cluster size distributions (Miller 1996, Miller 2000 and Tsong 2005).

The use of a laser causes the needle shaped specimen to temporarily warm up and if this heat is not efficiently removed before the next laser pulse, the continuous temperature rise causes deterioration in the spectrum resolution (atoms start evaporating between pulses) and can also result in tip damage. Furthermore, the stress that is involved in these measurements (high voltage and pulses) result into frequent tip fractures. Sample preparation can be challenging and is very labor intensive. It is one of the most critical steps for a successful analysis. In addition, insulating materials are still a challenge to evaporate in APT and since each material has a different evaporation field, multilayered structures are difficult to analyze.

There is a lot of room for improvement in sample preparation procedures, hardware (e.g., detection system) and the 3D reconstruction procedures. Despite those limitations the combination of atomic resolution and high sensitivity makes APT one of the very few techniques that can analyze nanometer scaled features in three dimensions.

Rutherford Backscattering Spectrometry

In Rutherford Backscattering Spectrometry (RBS) a specimen is bombarded with a highly energetic ion beam, usually MeV He ions. The energy distribution of the backscattered ions is recorded providing a quantitative determination of the material as a function of depth.

As the incident ions collide with the specimen atoms, energy is transferred from the projectile to the stationary target atom. The amount of energy loss depends on the masses of the incident ion and the atom it underwent a collision with. RBS is non destructive, does not need standards to quantify its results, has a depth resolution of several nanometers and good sensitivity (ppm) for heavy elements. Both conductors and insulators can be easily analyzed and determine thin film composition and thickness or density if one of the two is known (Feldman 1986).

RBS is not as sensitive with light elements and other methods, such as nuclear reaction analysis need to be implemented. In addition, it requires a large area of analysis, usually about 2 millimeters and is insensitive to the electronic configuration and chemical bonding of the specimen.

Despite its limitations, due to its simplicity, accuracy and precision, RBS is widely used as the benchmark analytical technique and its results are often used as standards for calibrating other methods.

CRYSTAL STRUCTURE ANALYSIS

The crystal structure of a material is another property that is often analyzed, i.e., knowing the location and identity of atoms in three dimensions throughout the specimen. Solids can be single crystals, where all atoms are arranged in the same repeating manner, amorphous, where there is no specific ordering or polycrystalline, where there is short range but not long range symmetry.

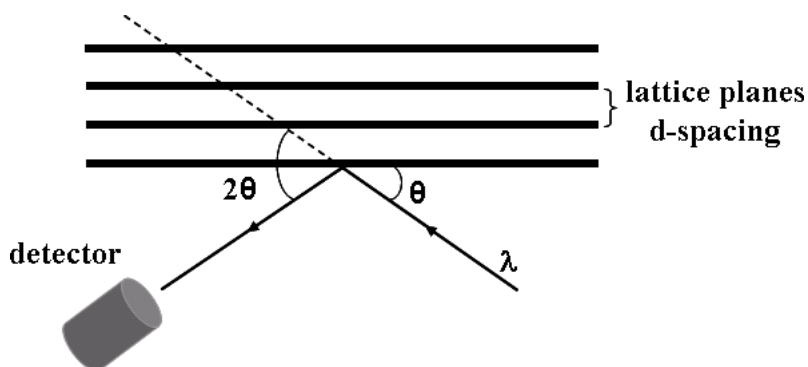
X-Ray Diffraction

In X-ray Diffraction (XRD), a specimen is irradiated with an incident beam of monochromatic X-rays of wavelength λ which is diffracted to specific directions that depend on atom arrangement. As X-rays strike the sample at a given incident angle, some are reflected and some keep traveling into the specimen. X-rays that traveled deeper into the material can be reflected from atomic planes formed by the ordered atoms. If the traveled distance between planes differs by an integer number of wavelengths then constructive interference occurs (diffraction), otherwise destructive interference takes place and nothing is measured by the detection system. Bragg's law summarizes the above into the following equation:

$$2d\sin\theta = n\lambda \quad (5)$$

where d is the lattice plane spacing and θ is the angle between the incident X-ray and the scattering planes as shown in Figure 4. Using a goniometer the angle θ can be varied, satisfying Bragg's law for different lattice spacings, therefore examining the material for different phases, crystal orientations and in certain cases grain sizes in thin films (Cullity and Stock 2001).

Figure 4. X-rays of wavelength λ that are reflected from successive planes have traveled distances that differ by $2d\sin\theta$. For constructive interference this difference in path length needs to be equal to $n\lambda$, where n is an integer.



Little or no sample preparation is required to obtain information such as crystal orientation, thickness and strain of thin epitaxial films. XRD is non destructive and does not require vacuum, however, the lateral resolution is of the order of several micrometers or millimeters (typically 50 micrometers or more for lab instruments).

ELECTRON BEAM DIFFRACTION

Due to the large X-ray spot sizes, XRD can analyze blanket films or large structures. If the crystallinity of small structures is required, then electron beam diffraction is the solution. Diffraction patterns can be collected in a TEM or by analyzing the Kikuchi patterns using Electron Backscatter Diffraction (EBSD) in an SEM.

CONCLUSION

There is no one method that can provide a complete characterization of a material. Because of that, there are several analytical techniques, more than those summarized in this chapter, and all of them have distinct capabilities, advantages and

disadvantages. It is important that the analyst understands the limitations of each technique and use the appropriate one or combination to obtain the desired answers. The type of sample, data that is needed and instrument availability will dictate the best approach. Furthermore, with the increased calculation capacity that computers have these days, the combination of analytical and simulation techniques, such as Monte Carlo modeling (Gauvin 2006 and Sempau 1997), has proven to be very helpful in solving complex problems.

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KEY TERMS AND DEFINITIONS

Analytical Technique: An analytical technique is a procedure used to determine material properties.

Characterization: Characterization in materials science refers to the procedure of using a series of analytical techniques.

Composition: Composition refers to identity and fraction of each element/ingredient present in a material.

Crystal Structure: Crystal structure refers to the arrangement of atoms in a material.

Imaging: Imaging is the visual representation of an objects property.

Quantitative Analysis: Quantitative analysis is a procedure used to determine the fraction of each element in a material.

Qualitative Analysis: Qualitative analysis is a procedure used to determine what elements are present in a material.

Chapter 12

Mechatronics Technology for Solar Cells

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ABSTRACT

A mechatronic real-time solar tracker is developed with National Instruments Compact Rio programming module, photoresistors sensor, stepper motors, and a set of nickel metal hydride (NiMH) cells. The tracking array is able to pivot on two axes by way of the stepper motors to reflect the effect of daily and seasonal trajectories of the sun. This design will keep the solar cell perpendicular to the sunlight. This project furthers the application of mechatronics to the field of renewable energy.

INTRODUCTION

The environmental impact of depleting the carbon based fossil fuels and the finite availability of these resources have been urging the researchers to investigate the alternative sources of energy for decades of years. As our current utility systems are based on the burning of carbon fuels environmentalists are studying the effects on the environment. These types of energy utilities produce greenhouse gasses. As energy demand rises, the production of greenhouse gasses will also rise. With the exponential growth of the population and the continued depletion of carbon-based fossil

fuels, alternative power sources must be realized. The advancements in energy storage and system control tools allow alternative energies to be more viable solutions than in the past.

As one of the largest green, renewable and sustainable energy sources available on our planet, the solar energy, whose average incident power is about 1000 W/m^2 can be converted into electric energy via the photovoltaic cells which are exposed to sunlight. Among the converters or producers of alternative energies, “solar cells have no known adverse environmental impacts during operation, while coal power produces sulfur and acid rain, nitrogen oxides, coal dust, and carbon

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dioxide, and nuclear power produces wastes that are dangerous for thousands of years and can be used to make nuclear bombs, solar cells have none of these hazards.” (Pinkerton and Rose, 1981) Only a small amount of waste is created during the manufacturing process of solar cells. This low one time environmental impact of solar cells is significantly less than that of other power sources.

New technologies developed enhance the viability of renewable energy as an alternative energy. The industry of photovoltaics has experienced enormous growth in the past decade. Photovoltaic cells gained the market share in successive years. Aronson has identified the following “categories of solar power systems”: (1) Multimegawatt systems supplying large facilities or towns; (2) Commercial systems that supplement grid power or are the only power source for a single building; (3) Single residential systems to power a single home or farm. Solar power units are now produced in three general configurations: flat-plate photovoltaic (PV) cell, concentrator design, and non-photocell version of the concentrator. (Aronson, 2009)

In solar energy utilization, researchers explore several methods to improve the efficiency of photovoltaic cells. Some applications of machine intelligence to solar energy are surveyed as follows: Solar collection yields a low amount of electrical energy. Studies have shown that on large systems uneven collection can cause some solar cells to act as resistive loads on the system. This can significantly impact the system’s output. There have been several applications of machine intelligence to improve system efficiency. This is commonly referred to as maximum power point tracking (MPPT).

In the study by Roman et al. (2006), a PV array with 20 PV modules were wired in series for a residential rooftop application. It is stated that avoidance of partial shading in this environment is not always attainable. A substantial reduction of the system performance is resulted by trees, buildings, television aerials, and other roof structures.

For this study, five of the 20 PV modules were installed in the shadow of a chimney, and when connected in series PV modules are forced to draw the same current. The shaded modules would act as passive loads. The system is proposed to utilize machine intelligence to determine which modules had low power output and disconnected them from the system. This increased the efficiency of the system.

Houssamo et al. (2010) compared their adaptive perturbation and observation (P&O) algorithm to the incremental conductance (INC) algorithm for maximum power point tracking. The P & O algorithm utilizes a voltage difference, while the incremental conductance (INC) algorithm utilizes the derivative of the photovoltaic system impedance. Two identical photovoltaic systems were set up consisting of eight solar panels each programmed to perform one of the two algorithms. The feedback data was the load impedance of the photovoltaic system. The systems made adjustments through the use of four DC-DC converters. It is found that the properly optimized P&O method has “mostly the same MPPT efficiencies as INC method, and is highly competitive against other MPPT algorithms by its easy implementation.”

Jalili-Kharaajoo (2004) conducted a study on a solar thermal power plant. The effects of a neuro-fuzzy controller to adjust the flow rate of oil, which was heated for a solar thermal power plant. It is reported that “thermal energy storage in the tank can subsequently used to produce electrical energy in a conventional steam turbine/generator or in a solar desalination plant operation.”

Another approach is the attitude control of the photovoltaic cells, and it also helps to produce the maximum energy on a given solar panel. The solar panel is kept directly facing the sun, so that the surface normal of the solar panel is parallel to the sunlights every moment in any day of the year. Mechatronic solar tracking system is a natural choice to cope with the sun movement from sunrise to sunset and the seasonal variation of sun trajectories during the year, and the functions of

such a solar tracker requires multiple degree of freedom (DOF). There are several ways to design mechatronic solar tracking systems to serve the purpose. In general, the solar panel attitude controls can be realized mainly by two types of approaches: (1) using the time operated tracking techniques; (2) using the sensing and alignment techniques. In the former approach, the attitude of the solar panel is adjusted by the system microcontroller via electric motors and their drives according to the trajectory data of the sun stored in the IC memory chip. In the latter approach, the solar position is determined by sensors, through which the microcontroller adjust the photovoltaic panel's attitude via electric motors and their drives. The following survey presents some of these realizations.

In 2008, Al-Soud et al. developed a parabolic solar cooker that automatically tracked the sun. The cooker consisted of a parabolic array of mirrors focusing on a black steel tube in the center. Two motors controlled the tilt and rotation of the cooker. Water was pumped into the black steel tube on one end and exited the other end. A PLC controlled the system and adjusted the cooker based on previously calculated solar angles. Incremental position adjustments were made in 10-20 minute increments on the horizontal axis and 15-35 minute increments on the vertical axis. The parabolic solar cooker heated the tube water to temperatures of 90° C. This is an applications of the time operated tracking techniques.

The simplest and most efficient technique to maximize the collection potential of a solar cell is to have line of sight orientation with the sun. This maximizes the exposure potential of the collection surface. The effectiveness and importance have been realized by researchers. Lee et al. [2009] said, "it is necessary to track the sun to a high degree of accuracy." When the PV system is oriented at a right angle the optimal energy collection can be realized. (Sungur, 2008)

A study conducted by Lee et al. [2009] focused on the potential energy gain by various closed-

loop and open-loop control algorithms. These various tracking methods were compared to a non-tracking system. It concluded, "compared to their traditional fixed-position counterparts, solar systems which track the changes in the sun's trajectory over the course of a day collect far greater amount of solar energy, and therefore generate significantly higher output power."

Zhang et al. (2007) studied the applications of a FPGA development board to intelligent solar tracking. Utilizing the Nios II Embedded Processor, they developed a solar tracking system. A stationary sensor tower collected sensory data in real-time to calculate the correct orientation to tilt the cells. The experiment was tested by comparing collection capacity of the unit when it was stationary to when it was dynamic. The results of the experiment yielded 59,904 J more than the array as a stationary unit. Zhang et al. claimed, "This system can achieve the maximum illumination and energy concentration and cut the cost of electricity by requiring fewer solar panels, therefore, it has great significance for research and development."

Sungur (2008) studied the application of a PLC to intelligent solar tracking. His prototype used photosensors and an algorithm applying solar angles to solar tracking. These angles were derived by the PLC based on local latitude and time of year. Sungur said, "in these photosensor systems used, unstable states may exist under overcast and partly cloudy weather conditions when the photosensors do not see the sun."

Woodward (2008) analyzed the maximum power point tracking control algorithm perturb and observe. He states, "The perturb-and-observe algorithm is the basis of the maximum power point tracking control circuit but with a twist which achieves a feedback function equivalent to a current times voltage power calculation but without the complexity of a conventional multiplier." The two conditions required for this relationship are the logarithmic behavior of transistor junctions and the mathematics of adding logarithms.

Sefa et al. (2009) designed a single axis sun tracking system in Turkey. The sun tracking system developed by Sefa and others included a serial communication interface based on Rs 485 to monitor whole processes on a computer and record the data. Feedback data was recorded by two photo resistors. The solar cell was aligned at a fixed 41° facing the south. A microcontroller observed and controlled the east-west rotation of the tracker by means of 24V 50W dc motor. The results of the measured energy showed an increase up to 46.46% of collected solar energy.

Oner et al. (2009) developed a solar tracker utilizing the application of a spherical motor. The motor contains a rotor containing a four pole magnet surrounded by eight individually energized stator poles. With the magnet in the middle direction is controlled by the surrounding stator poles. This design allows for three degrees of freedom. The degrees of freedom being forward and back tilt, a left and right lateral tilt, and rotation along a z-axis. Feedback data is recorded by two phototransistors in the middle of the top and left side of the solar panel. The feedback data is fed into a PIC 16F877 micro-controller for directional adjustments. The control logic of the micro-controller adjusted the solar panel in increments in 5°. By utilizing a spherical motor allows for one motor to perform the same function gained by two conventional motors.

An article by Presher (2010) reported recent developments in the applications of solar tracking. Reliathon, a Suntech Power Holding, developed a solar tracking system, Duratrack for utility scale solar plants in 2010. He claimed, “what makes the DuraTrack solar tracker unique from other companies in horizontal axis tracking for the utility market is the drive system. Other horizontal tracking systems use a push/pull linkage to move many rows with one linear actuator or motorized drive, while Array Technologies’ design uses a rotating drive linkage.” The flexible drive

allows for installation of the Duratrack system over various terrains with ease. The drive line rotates the panels from east to west. The system is controlled by a PLC utilizing sensory data from GPS inputs. The Duratrack system comes in two models, one 0 degree tilt and one 20 degree tilt. Presher quotes Brian MacCleery, a senior product manager at National Instruments who focuses on green and renewable energy projects stating, “one of the drivers in solar tracking is the emergence of concentrated photovoltaics. Because the optics used in these systems magnify and concentrate the sunlight onto a small solar cell, they require very precise two-axis tracking of the sun to achieve peak output”. MacCleery continues citing research conducted at the Applied Research Center for Intelligent Control and Automation. MacCleery states the research being done utilizes Labview in combination with SolidWorks to create virtual prototypes of sun tracking systems. (Presher, 2010)

In 2010 another solar tracking system was designed by Barsoum and Vasant at Curtin University in Sarawak, Malaysia. Their prototype utilized a control circuit based on a PIC16F84A microcontroller. The prototype utilized feedback data collected from four cadmium sulfide photo resistors. The cadmium sulfide photo resistors were selected based on darkness and light saturation resistance. A perpendicular obstruction was placed between any given pair of photo resistors. The purpose was to increase the voltage difference between any given pairs not perpendicularly aligned. The tracker aligning was performed by two 12 volt motors. The motors drove the alignment utilizing a chain gear system to produce the necessary torque. They said, “a lot of time was needed to be set aside for verification and testing due to the unpredictability of weather and debugging issues.”

Ghosh et al. (2010) studied how the orientation and tilt angle of a solar cell affected performance of a solar radiation conversion system. They uti-

lized three mathematical models- the Isotropic, the Klucher and the Perez model to determine hourly and seasonal optimum tilt angles. The Isotropic model is a simplified model. In the Klucher model the cloud conditions are adjusted for. The Perez model is designed to compensate for a variety of weather conditions. The three models were evaluated for accuracy by having their root mean square, bias error, and mean relative percentage error. The anisotropic Perez model resulted in the smallest root mean square reading 0.09 for monthly tilt factor. It is stated that “the results demonstrated that a gain in the amount of solar radiation received by the surface mounted tilt angle at monthly tilt angle lied in the range of 0%–55%.”

The research surrounding solar energy has a brief history of rapid growth. Bell Telephone Laboratories originally created Solar Cells during the 1970s (Nansen, 1995). Utilization of this developing technology may lead to long-term solutions to the growing energy crisis.

With the continued damage to the environment and growth of energy demands new sources of energy must be realized for continued prosperity. Experts can all agree that two basic criteria must be observed to be considered a viable option. Energy must be low cost and reliable. Other criteria to be considered are environmental effects and usability of the type of energy. (Aronson, 2009; Nanson, 1995) Aronson (2009) said: “Solar and wind energy, classified as intermittent power, are potential sources of tremendous energy. But, the long-standing challenge is converting that energy into usable power.”

In this chapter, we will focus on the design of this 2 DOF mechatronic solar tracker controlled with sensing and alignment techniques to harness this renewable energy source. A solar tracking array fitted with photovoltaic panels will be designed to adjust solar collecting positions dynamically. The solar tracking device with higher efficiencies and lower cost should endure various kinds of weather conditions.

DESIGN OF A SOLAR TRACKER

This research project is to access the application of Mechtronics to enhance the viability of solar energy as an alternative energy source. The type of research done in this project will be quantitative. Equipment for this experiment include two solar panels of equal size and output ratings, three equal sets of nickel metal hydride cells, and a real-time prototype solar tracking array. Each solar panel will feed directly into to a set of nickel metal hydride cells. The third set of nickel metal hydride cells will power the solar tracking unit. For each trial the stationary solar panel will collect energy within 10 feet of the solar tracking unit for a period of 12 hours. At the end of the tracking period, the energy will be recorded. The study will include 10 trials. Any trials to be stopped due to inclimate weather shall be recorded with their exposure time. Descriptive statistics will be performed on the data. This will develop an overall differential in collection tendencies.

The researchers at Purdue University fabricate the real-time solar tracking array using control laws with a National Instruments Compact Rio (NI CRio) programming module, three photoresistors sensors, two DC motors, and a set of NiMH cells. The tracking array is able to pivot on two axes to reflect the effect of daily and seasonal trajectories of the sun. The NI CRio programming module is programmed in Labview. The control logic will have the three sensors mounted to the solar cell taking measurements and comparing their signals. As the solar cell tilts, new measurements are taken. If the measurement is different, then the solar tracker will adjust in that direction and take another measurement. If not, it will remain in its current position. This design will provide the optimal collecting potential fixing the solar cell perpendicular to the sun. There is possible tilt instability due to overcast conditions. This project furthers the application of mechatronics to the field of renewable energy. Utilizing the NI CRio allows the use of Labview programming further demonstrating its flexibility (see Figure 1).

PROGRAMMING OF A SOLAR TRACKER

A closed programming loop will be used based on feedback principles. The three cadmium sulfide photo resistors will be the inputs. The Compact Rio is programmed so it can obtain the resistance data from the photo resistors and turn left or right, tilt forward or backward. The Compact Rio processing power is far greater than required for this task. Realizing the performance may be too fast a delay timer is needed. Barsoum and Vasant [2010] state, “the drawbacks associated with high frequency clock are: their requirement for large power consumption and also possibly the electromagnetic interference (p. 155)”

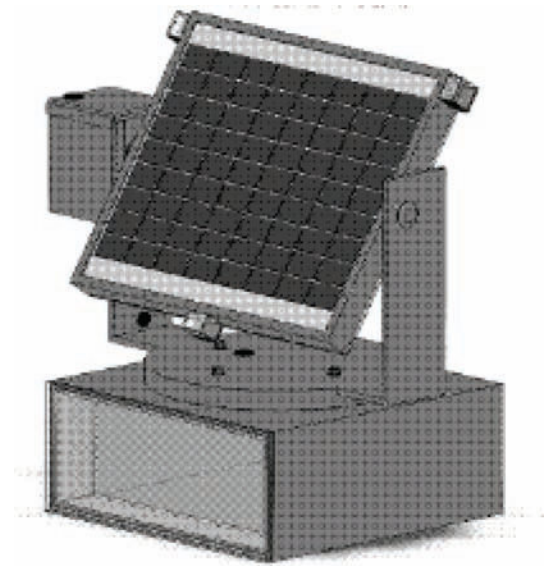
The Labview program for the sun tracker is used to gather sensor data and send corresponding control signals to the DC motors in order to minimize the angle of incidence between the incoming light and the solar panel.

In the sun tracker system, three photo resistors are installed on the solar panel to sense the luminous intensity, with two on each of the top sides and one on the bottom. The output signals of the photo resistors are corresponding analog voltage signals. As a dual axis sun tracker, two DC motors are used to control the orientation and tilt angle of the solar panel, and their input signals are PWM wave.

Labview NI cRIO 9012 is chosen as the controller. Moreover, considering the hardware inputs and outputs, proper control modules should be chosen too to plug in the controller slots. In order to gather analog signals from photo resistors, NI 9201 module is used to interface with them, while two NI 9505 modules are used to output PWM control signals to the two DC motors.

Since the program needs to communicate with peripheral hardware, Labview FPGA project is used to build this connection between software and hardware. This program includes two VIs, FPGA VI for interfacing with hardware by inputting analog signals and outputting PWM signals,

Figure 1. Design of solar tracker



and main control VI for talking with FPGA VI to make control decision based on the collected input signals and sending out the control signals.

Figures 2 and 3 show the block diagram and front panel of FPGA VI. In the block diagram, there are four frames inside. The top left one is the program module for collecting analog signal from NI 9201, with the sampling frequency 25 Hz. The top right module is controlling the FPGA led on NI cRIO 9012 to make sure the controller is working all right when it blinks. The other two modules are exactly the same, which are used for NI 9505 to get the control signals from control VI and output the PWM wave to the two DC motors. The real time input signals and control signals can be read from the front panel.

Figures 4 and 5 show block diagram and front panel of control VI. The block diagram reads the input analog signals from the FPGA VI, and decides the corresponding control signals based on its designed control laws. The control laws used here are built upon the comparisons between the three groups of input data: comparison between the signals from top left and top right photo resistors for orientation control, while comparison

Figure 2. Block diagram of FPGA VI

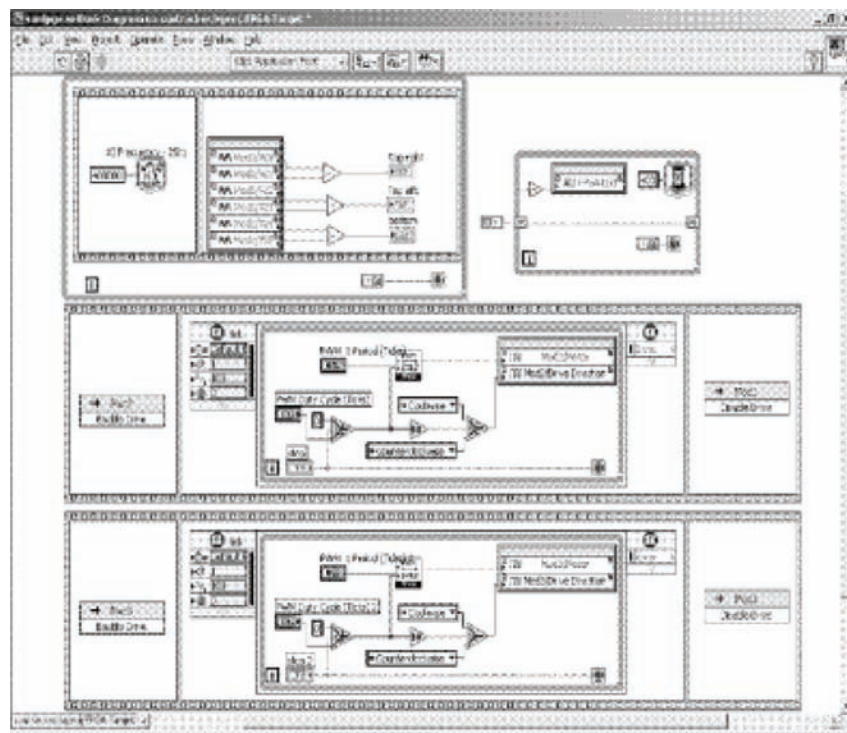


Figure 3. Front panel of FPGA VI

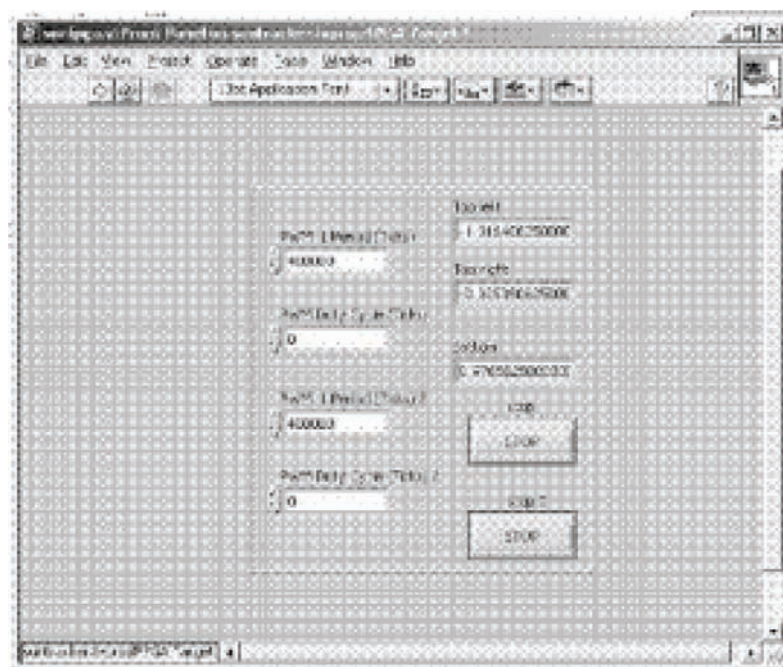


Figure 4. Block diagram of control VI

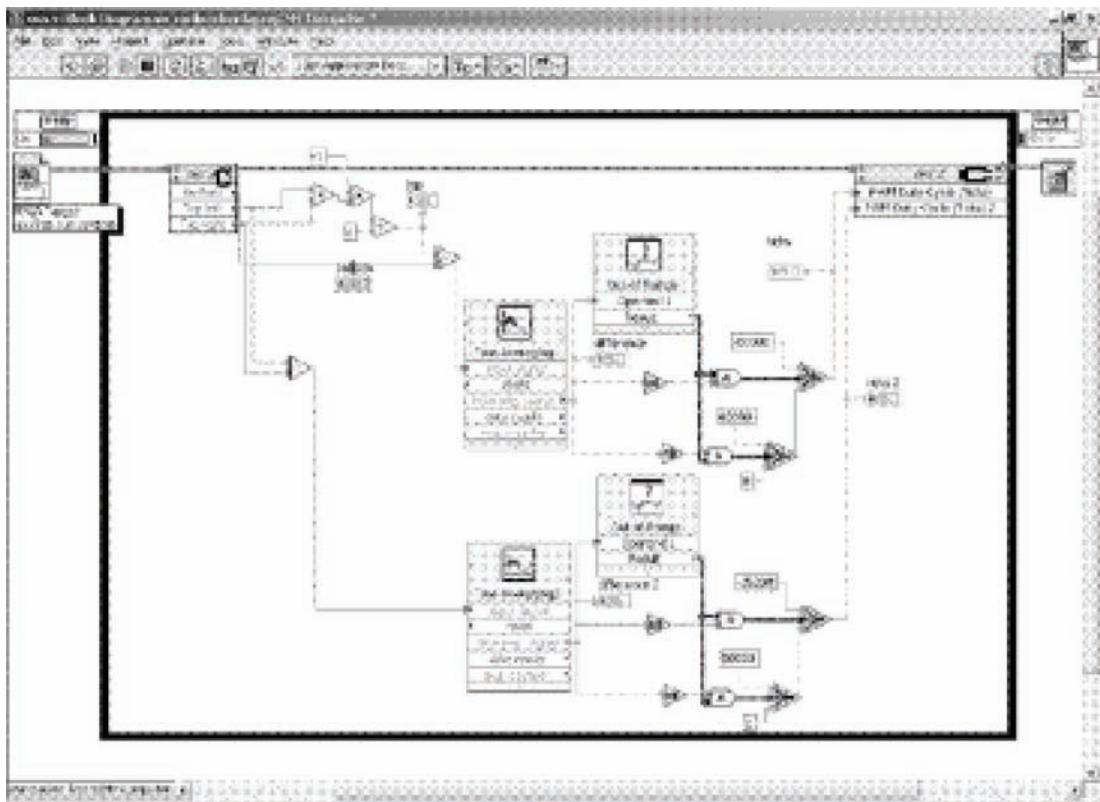
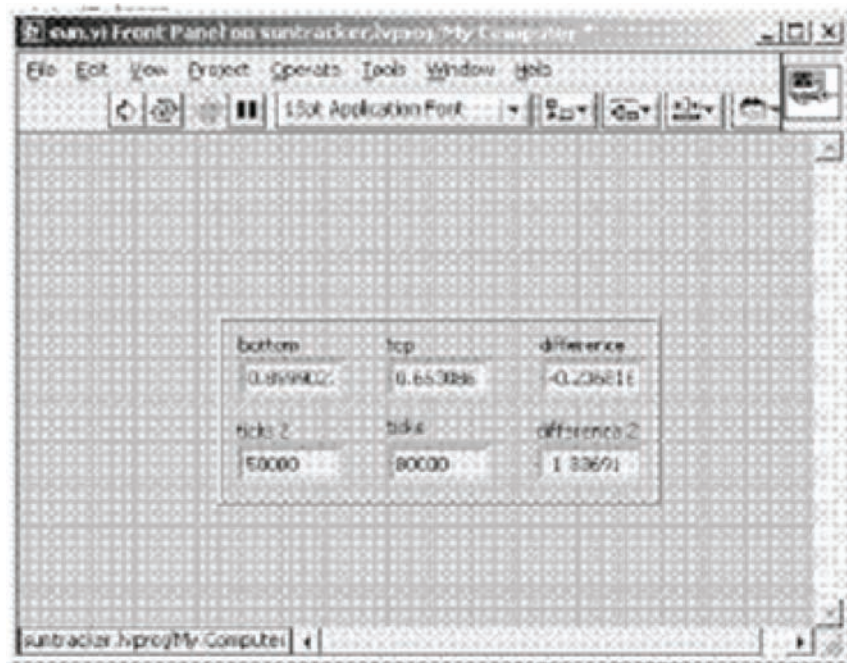


Figure 5. Front panel of control VI



between the bottom signal and average signal of top left and top right photo resistors for tilt angle control. In order to avoid noise, averaged comparison results are preferred and designed in this program. The control signals sent from the control VI to FPGA VI are PWM duty cycle ticks, which could be positive, zero and negative numbers. Since the sun tracker should be working in a slow mode, the amount of differences are not used in the program to determine the duty cycle ticks of the PWM wave when the differences are not zero, which means the duty cycle ticks of the PWM wave is constant in this program without the sign, furthermore, the amount of difference only decides the moving direction and the time that costs to arrive at the desired status. The front panel of control VI gives the real time results of the comparisons and the PWM duty cycle ticks sent to the FPAG VI in order to monitor the data exchange between the Vis and the control decisions.

PROTOTYPE AND EXPERIMENTS

It is demonstrated that the energy gained from optimal collection will exceed the energy requirement of continuous monitoring and adjustment. The harnessing of solar photovoltaics energy has many aspects that may be refined. There are electrical circuit inefficiencies in large grid systems, losses from physical positioning, and a lower energy yield. The project scope will be further narrowed to losses from physical positioning.

In the design of this 2 DOF mechatronic solar tracker, the relative components were sealed so that they are weatherproofed. Wheels are mounted to hold up the panel and rotate around the vertical axis. There is another motor attached to the side of the panel and have that rotates the panel across the horizontal axis. The rest of the system components function properly, and efficiently. Two light weight and compact motors are selected.

The rotation about the vertical axis is guaranteed using the wheels and a corrosion-resistant

turntable. The friction is small enough to be neglected, the rotation is smooth. The turntable also made the tracker have the ability to stop in a more precise spot with a smaller movement.

The researcher will fabricate the proposed real-time solar tracking array. The various parts required for the array are framing, a National Instruments Compact Rio programming module, three optical sensors, one dc motor, one stepper motor, and one set of nickel metal hydride cells. The tracking array will be able to pivot on a tilting axis by way of a 12 volt DC motor with attached gear box. The tracking array rotation will be performed by the stepper motor. The National Instruments Compact Rio programming module will be programmed in Labview 8.6.

The Feedback Design will utilize cadmium sulfide photo resistors as the optical sensors. The cadmium sulfide photo resistors were selected for their simplicity and availability. The photo resistors are to be aligned on the top and bottom of the solar cell. Attached to the back side of the solar cell the photo resistors are shimmed to half the height of the thickness of the solar cell. This is to create a larger differential between the voltage of top and bottom. It was assumed that the distance between the left and right photo resistors will already have a large enough voltage difference.

The primary unit of interest is volts collected. This will be measured by using a volt meter to check the voltage of the nickel metal hydride cells. Other units of interest will be foot-candle levels in the interest of calibrating any potential differences in static readings. For these readings a Type 214 General Electric light meter will be used.

Solar collection data was taken for seven days. On the first day of energy collection it was discovered that the solar tracker was unable to determine a distinction in left right sensor readings. In an attempt to increase this distinction, the dead zone in the program was reduced allowing the most minor differences to activate motor direction. The result was unsuccessful causing a continuous clockwise rotation and a seesaw motion by the tilt

motor. During the second day of energy collection the dead zone in the program was made slightly larger. This allowed a difference in tilt readings; however the difference in left right readings was completely in the program's dead zone. This data as unintended provided useful insight as to the tendencies of the solar tracking system. From the voltage data in table 5.1, it is seen that the voltage drained by the non-operating motor (M2 Batt) was significantly close to that of the utilized tilt motor (M1 Batt). These findings suggest that as built the solar tracking system would not experience significant power savings using periodic data. Trial two was ended early to develop a way to incorporate rotation into the motion. Before the third day of energy collection shades were added to the solar tracker. This allowed the left right readings to have a differential and allowed rotation as well as tilt. Energy collection days five to seven serve as a control of the stationary collector. Trials five and six were ended prematurely due to rain. The results have shown that a 28% increase in voltage collected with solar tracking.

CONCLUSION

The purpose of this was to design and implement a two-axis solar tracking system utilizing the National Instruments C-Rio real time controller. In order to accomplish this a prototype was modeled in CAD. This prototype used two 12 VDC motors to change a solar panel's rotation and tilt based on feedback data from three cadmium sulfide photoresistors. This configuration was chosen for its ability to create both a left-right rotational and an up/down tilt differential. In Addition this approach uses National Instruments Labview to control a solar tracking system. Using Labview add uniqueness to this project by adding a graphical programming approach instead of conventional text based coding.

Solar collection data was taken for seven days. During the energy collection performed on the first day and the second day the sensitivity was calibrated for outdoor conditions. The results have shown that a 28% increase in energy collected with solar tracking, however due to the energy demands of C- Rio controller and motors the net energy gains were less than a stationary collector.

This project has resulted in a working solar tracking prototype. With a few design modifications an upgrade to this system may prove useful in future research. With the growing complexity of technology, interest in mechatronics will continue to develop requiring further research will be necessary. Therefore, this project provides Purdue University with demonstration prototype in the up and coming field of mechatronics.

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KEY TERMS AND DEFINITIONS

Compact Rio: The CompactRIO is a programmable automation controller of National Instruments. It is a reconfigurable control and acquisition system, and combines an open embedded architecture with compact size, and industrial I/O modules.

FPGA: FPGA stands for field-programmable gate array. An FPGA is an integrated circuit that supports thousands of identical logic cells interconnected by a matrix of wires and programmable switches. The array of logic cells and interconnect form a fabric of basic building blocks for logic circuits. A user desired circuit can be realized by specifying simple logic functions for the cells and switching to form the interconnect matrix.

Mechatronics: Mechatronics is an interdisciplinary system, composed of electrical, electronic, mechanical, structural and control subsystems and their interfacing, integrated with real-time microprocessor / controller operations.

Solar Energy: solar energy is the energy of solar radiation that is carried to the earth via sun beams. It can be converted into heat and electric-

ity, and it is the most available and sustainable energy source to the earth.

Solar Tracker: The attitude of the solar panel composed of photovoltaic cells is controlled to track the sun movement from sunrise to sunset and the seasonal variation of sun trajectories during the year, so that the solar panel produces the maximum energy on the solar panel.

Chapter 13

Computer Simulations of Solar Energy Systems

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ABSTRACT

In recent years, computer simulation has become a standard tool for analyzing solar energy systems. The interaction of light with nanoscale matter can provide greater functionality for photonic devices and render unique information about their structural and dynamical properties. As the field of nanophotonics continues to experience phenomenal growth at both the fundamental research and applications level, computational modeling is essential both for interpreting experiments and for suggesting new directions – for example, in designing of thin-film photovoltaic cells. The demand for computer simulation continues to increase as researchers and developers tackle the tough challenges of designing new generation devices and optimizing current generation devices. This chapter is devoted to the development and application of the Finite-Difference Time-Domain (FDTD) method to solar energy systems. In addition, new models covering the latest advances in nanophotonics technologies, as well as key improvements to the numeric solvers and new usability features, are introduced in this chapter.

INTRODUCTION

Thin-film solar cells offer the possibility to improve efficiencies and lower costs in next generation photovoltaic devices. Further, light trapping is the standard technique for improving solar cell efficiencies and for harvesting the spectrum of incoming sunlight.

In order to describe the propagation and scattering of sunlight within the solar cell and optimize the process, Maxwell's equations have to be rigorously solved. Some of the well-adopted simulations for optical simulations are the finite difference time domain (FDTD) method (Qiu and He, 2000; Farjadpour *et al.*, 2006; Ong *et al.*, 2007; Tsakalakos *et al.*, 2007), the transfer matrix (TM) method (Hu and Chen, 2007), and scattering theory (Street *et al.*, 2008).

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This chapter is devoted to the development and application of the finite-difference time-domain (FDTD) method to solar energy systems. In addition, new models covering the latest advances in nanophotonics technologies, as well as key improvements to the numeric solvers and new usability features are introduced in this chapter.

FINITE DIFFERENCE TIME DOMAIN (FDTD) METHOD

The FDTD method numerically solves Maxwell's curl equations by representing time and spatial derivatives as finite differences. The basic Maxwell's curl equations in a three dimensional (3D) domain are expressed as (Taflove & Hagness, 2000):

$$\frac{\partial \vec{E}}{\partial t} = \frac{1}{\varepsilon} \nabla \times \vec{H} - \frac{\sigma}{\varepsilon} \vec{E} \quad (1)$$

$$\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu} \nabla \times \vec{E} \quad (2)$$

where both the electric field $\vec{E}$ and magnetic field $\vec{H}$ describe the interaction between light and the solar cell. The solar cell is described by its permittivity ε and permeability μ . The parameters, $\varepsilon = \varepsilon_r \varepsilon_o$ and σ describe the optical properties of the solar cell. Expanding the curl operator in (1) and (2) and equating their respective vector components on each side appropriately, these equations can be represented with the following six equations in a Cartesian coordinate system (x, y, z) :

$$\frac{\partial H_x}{\partial t} = -\frac{1}{\mu} \left[\frac{\partial E_z}{\partial y} - \frac{\partial E_y}{\partial z} \right] \quad (3)$$

$$\frac{\partial H_y}{\partial t} = -\frac{1}{\mu} \left[\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} \right] \quad (4)$$

$$\frac{\partial H_z}{\partial t} = -\frac{1}{\mu} \left[\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} \right] \quad (5)$$

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon} \left[\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \sigma E_x \right] \quad (6)$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon} \left[\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \sigma E_y \right] \quad (7)$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon} \left[\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \sigma E_z \right] \quad (8)$$

The FDTD algorithm divides the problem geometry into a spatial grid where electric and magnetic field components are placed at certain discrete positions in space, and it solves Maxwell's equations in time at discrete time instances (Taflove & Brodwin, 1975; Yee, 1966). Grid coordinates on a uniform, rectangular FDTD mesh are defined as:

$$(i, j, k) = (i\Delta x, j\Delta y, k\Delta z) \quad (9)$$

in which Δx , Δy , and Δz represent the physical dimensions of each grid cell. Furthermore, any function with temporal and spatial variations can be generally expressed as:

$$s_{i,j,k}^n = (i\Delta x, j\Delta y, k\Delta z) \quad (10)$$

with Δt denoting the time-step and n the corresponding time index. Using this notation, the time and space derivatives of s in central-difference form can be written as:

$$\frac{\partial s_{i,j,k}^n}{\partial x} = \frac{s_{i+\frac{1}{2},j,k}^n - s_{i-\frac{1}{2},j,k}^n}{\Delta x} + O[(\Delta x)^2] \quad (11)$$

$$\frac{\partial s_{i,j,k}^n}{\partial t} = \frac{\partial s_{i,j,k}^{n+\frac{1}{2}} - \partial s_{i,j,k}^{n-\frac{1}{2}}}{\Delta t} + O[(\Delta t)^2] \quad (12)$$

where $O[(\Delta x)^2]$ and $O[(\Delta t)^2]$ represent the second order terms. Applying these central-difference approximations to Equations (3) through (8), results in the following set of six, explicitly coupled, finite-difference update equations:

$$H_x \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^{n+\frac{1}{2}} = H_x \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^{n-\frac{1}{2}} + \left(\frac{\Delta t}{\mu_{i,j+\frac{1}{2},k+\frac{1}{2}}} \right) \times \left[\left(\frac{E_y \Big|_{i,j+\frac{1}{2},k+1}^n - E_y \Big|_{i,j+\frac{1}{2},k}^n}{\Delta z} \right) - \left(\frac{E_z \Big|_{i,j+1,k+\frac{1}{2}}^n - E_z \Big|_{i,j,k+\frac{1}{2}}^n}{\Delta y} \right) \right] \quad (13)$$

$$H_y \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n+\frac{1}{2}} = H_y \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n-\frac{1}{2}} + \left(\frac{\Delta t}{\mu_{i+\frac{1}{2},j,k+\frac{1}{2}}} \right) \times \left[\left(\frac{E_z \Big|_{i+1,j,k+\frac{1}{2}}^n - E_z \Big|_{i,j,k+\frac{1}{2}}^n}{\Delta x} \right) - \left(\frac{E_x \Big|_{i+\frac{1}{2},j,k+1}^n - E_x \Big|_{i+\frac{1}{2},j,k}^n}{\Delta z} \right) \right] \quad (14)$$

$$H_z \Big|_{i+\frac{1}{2},j+\frac{1}{2},k}^{n+\frac{1}{2}} = H_z \Big|_{i+\frac{1}{2},j+\frac{1}{2},k}^{n-\frac{1}{2}} + \left(\frac{\Delta t}{\mu_{i+\frac{1}{2},j+\frac{1}{2},k}} \right) \times \left[\left(\frac{E_x \Big|_{i+\frac{1}{2},j+1,k}^n - E_x \Big|_{i+\frac{1}{2},j,k}^n}{\Delta y} \right) - \left(\frac{E_y \Big|_{i+1,j+\frac{1}{2},k}^n - E_y \Big|_{i,j+\frac{1}{2},k}^n}{\Delta x} \right) \right] \quad (15)$$

$$E_x \Big|_{i+\frac{1}{2},j,k}^{n+1} = \left(\frac{1 - \frac{\sigma_{i+\frac{1}{2},j,k} \Delta t}{2\varepsilon_{i+\frac{1}{2},j,k}}}{1 + \frac{\sigma_{i+\frac{1}{2},j,k} \Delta t}{2\varepsilon_{i+\frac{1}{2},j,k}}} \right) E_x \Big|_{i+\frac{1}{2},j,k}^n + \left(\frac{\frac{\Delta t}{\varepsilon_{i+\frac{1}{2},j,k}}}{1 + \frac{\sigma_{i+\frac{1}{2},j,k} \Delta t}{2\varepsilon_{i+\frac{1}{2},j,k}}} \right) \cdot \left[\left(\frac{H_z \Big|_{i+\frac{1}{2},j+\frac{1}{2},k}^{n+\frac{1}{2}} - H_z \Big|_{i+\frac{1}{2},j-\frac{1}{2},k}^{n+\frac{1}{2}}}{\Delta y} \right) - \left(\frac{H_y \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n+\frac{1}{2}} - H_y \Big|_{i+\frac{1}{2},j,k-\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta z} \right) \right] \quad (16)$$

$$E_y \Big|_{i,j+\frac{1}{2},k}^{n+1} = \left(\frac{1 - \frac{\sigma_{i,j+\frac{1}{2},k} \Delta t}{2\varepsilon_{i,j+\frac{1}{2},k}}}{1 + \frac{\sigma_{i,j+\frac{1}{2},k} \Delta t}{2\varepsilon_{i,j+\frac{1}{2},k}}} \right) E_y \Big|_{i,j+\frac{1}{2},k}^n + \left(\frac{\frac{\Delta t}{\varepsilon_{i,j+\frac{1}{2},k}}}{1 + \frac{\sigma_{i,j+\frac{1}{2},k} \Delta t}{2\varepsilon_{i,j+\frac{1}{2},k}}} \right) \cdot \left[\left(\frac{H_x \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^{n+\frac{1}{2}} - H_x \Big|_{i,j+\frac{1}{2},k-\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta z} \right) - \left(\frac{H_z \Big|_{i+\frac{1}{2},j+\frac{1}{2},k}^{n+\frac{1}{2}} - H_z \Big|_{i-\frac{1}{2},j+\frac{1}{2},k}^{n+\frac{1}{2}}}{\Delta x} \right) \right] \quad (17)$$

$$\begin{aligned}
 E_z \Big|_{i,j,k+\frac{1}{2}}^{n+1} = & \left(\frac{\sigma_{i,j,k+\frac{1}{2}} \Delta t}{1 - \frac{\sigma_{i,j,k+\frac{1}{2}} \Delta t}{2\varepsilon}} \right) E_z \Big|_{i,j,k+\frac{1}{2}}^n \\
 & + \left(\frac{\frac{\Delta t}{\varepsilon_{i,j,k+\frac{1}{2}}}}{1 + \frac{\sigma_{i,j,k+\frac{1}{2}} \Delta t}{2\varepsilon_{i,j,k+\frac{1}{2}}}} \right) \cdot \\
 & \left(\left(\frac{H_y \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n+\frac{1}{2}} - H_y \Big|_{i-\frac{1}{2},j,k+\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta x} \right) - \left(\frac{H_x \Big|_{i,j,k+\frac{1}{2}}^{n+\frac{1}{2}} - H_x \Big|_{i,j,k-\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta y} \right) \right)
 \end{aligned} \quad (18)$$

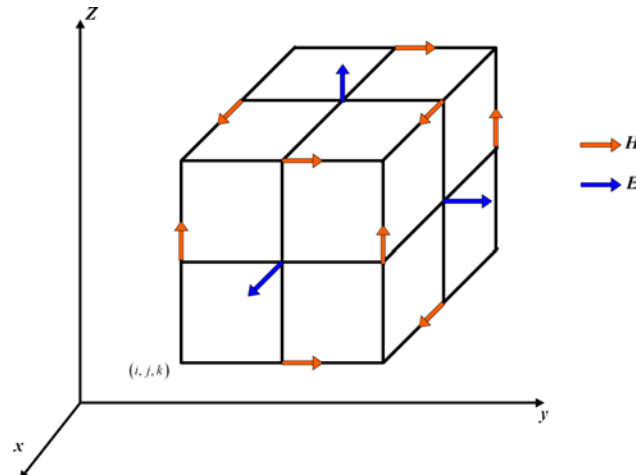
in which the electric and magnetic field components are spatially separated quantities that are interwoven in both space and time. The method for solving this system of finite-difference equations is often referred to as a “leapfrog” technique in which the field components are solved for and marched forward in time one after another,

and is the underlying mechanism enabling non-dissipative field propagation in this technique.

The six field components can be visualized as existing on two separate but interlaced grids occupying a single cubic unit cell in space. This space lattice, illustrated in Figure 1, is often referred to as a “Yee cell” (Yee, 1966). The electric field vector components are placed at the centers of the edges of the Yee cells and oriented parallel to the respective edges, and the magnetic field vector components are placed at the centers of the faces of the Yee cells and oriented normal to the respective faces. It can be easily noticed in Figure 1 that each magnetic field vector is surrounded by four electric field vectors that are curling around the magnetic field vector. Similarly, if the neighboring cells are also added to the figure, it would be apparent that each electric field vector is surrounded by four magnetic field vectors that are curling around the

electric field vector. Using either one of the visual representations, the origin (i,j,k) for both the electric and magnetic fields coincide with the origin at $(1,1,1)$. The color distinction between electric and magnetic fields is used to better highlight the fact that these field components exist on two interlaced, orthogonal grids.

Figure 1. Position of the electric field and magnetic field vector components in the Yee cell. The origin coincides with the point (i,j,k) .



During numerical simulation, the individual field components are updated and stored in large data arrays with indexed values designated by whole integers, not half-integer values as indicated in (13) through (18). Thus, in the actual programming code implementation the individual field components are referenced to the origin at (1,1,1) as are the half-integer values as well. This is done to simplify the equations making them easier to implement in a programming language such as MATLAB or FORTRAN. The actual programming code implementations of Equations (13) through (18) are given by:

$$\begin{aligned} H_x^{n+\frac{1}{2}}(i, j, k) &= H_x^{n-\frac{1}{2}}(i, j, k) \\ &+ db_{\Delta z}(i, j, k) [E_y^n(i, j, k+1) - E_y^n(i, j, k)] \\ &- db_{\Delta y}(i, j, k) [E_z^n(i, j+1, k) - E_z^n(i, j, k)] \end{aligned} \quad (19)$$

$$\begin{aligned} H_y^{n+\frac{1}{2}}(i, j, k) &= H_y^{n-\frac{1}{2}}(i, j, k) \\ &+ db_{\Delta x}(i, j, k) [E_z^n(i+1, j, k) - E_z^n(i, j, k)] \\ &- db_{\Delta z}(i, j, k) [E_x^n(i, j, k+1) - E_x^n(i, j, k)] \end{aligned} \quad (20)$$

$$\begin{aligned} H_z^{n+\frac{1}{2}}(i, j, k) &= H_z^{n-\frac{1}{2}}(i, j, k) \\ &+ db_{\Delta y}(i, j, k) [E_x^n(i, j+1, k) - E_x^n(i, j, k)] \\ &- db_{\Delta x}(i, j, k) [E_y^n(i+1, j, k) - E_y^n(i, j, k)] \end{aligned} \quad (21)$$

$$\begin{aligned} E_x^{n+1}(i, j, k) &= ca(i, j, k) E_x^n(i, j, k) \\ &+ cb_{\Delta y}(i, j, k) \left[H_z^{n+\frac{1}{2}}(i, j, k) - H_z^{n+\frac{1}{2}}(i, j-1, k) \right] \\ &- cb_{\Delta z}(i, j, k) \left[H_y^{n+\frac{1}{2}}(i, j, k) - H_y^{n+\frac{1}{2}}(i, j, k-1) \right] \end{aligned} \quad (22)$$

$$\begin{aligned} E_y^{n+1}(i, j, k) &= ca(i, j, k) E_y^n(i, j, k) \\ &+ cb_{\Delta z}(i, j, k) \left[H_x^{n+\frac{1}{2}}(i, j, k) - H_x^{n+\frac{1}{2}}(i, j, k-1) \right] \\ &- cb_{\Delta x}(i, j, k) \left[H_z^{n+\frac{1}{2}}(i, j, k) - H_z^{n+\frac{1}{2}}(i-1, j, k) \right] \end{aligned} \quad (23)$$

$$\begin{aligned} E_z^{n+1}(i, j, k) &= ca(i, j, k) E_z^n(i, j, k) \\ &+ cb_{\Delta x}(i, j, k) \left[H_y^{n+\frac{1}{2}}(i, j, k) - H_y^{n+\frac{1}{2}}(i-1, j, k) \right] \\ &- cb_{\Delta y}(i, j, k) \left[H_x^{n+\frac{1}{2}}(i, j, k) - H_x^{n+\frac{1}{2}}(i, j-1, k) \right] \end{aligned} \quad (24)$$

where the coefficients $db_{\Delta m}$, ca and $cb_{\Delta m}$ are defined as

$$db_{\Delta m}(i, j, k) = \frac{\Delta t}{\mu(i, j, k) \Delta m} \quad (25)$$

$$ca(i, j, k) = \frac{2\varepsilon(i, j, k) - \sigma(i, j, k) \Delta t}{2\varepsilon(i, j, k) + \sigma(i, j, k) \Delta t} \quad (26)$$

$$cb_{\Delta m} = \frac{2\Delta t / \Delta m}{2\varepsilon(i, j, k) + \sigma(i, j, k) \Delta t} \quad (27)$$

and $\Delta m = \Delta x, \Delta y$, or Δz .

NUMERICAL DISPERSION AND STABILITY

The general FDTD method discussed above is second-order accurate in both space and time. This follows directly from the Taylor series approximations used to express the temporal and spatial derivatives in (11) and (12). Finite discretization of Maxwell's equations and their subsequent solution on a lattice mesh results in nonphysical dispersion of the simulated wave propagation within the computational domain. Taflove (1975) was the first to present the correct

stability criteria for the original orthogonal-grid Yee algorithm (Taflove & Brodwin, 1975; Taflove & Hagness, 2000). Dispersion is the change in wavelength λ with frequency f (or the variation in wave number k with angular frequency ω). This phenomenon results in a change in the phase velocity of propagating waves that can vary with wavelength, grid discretization, and the direction of wave propagation along the grid. So, it is important to consider the spatial step, time step and their relationship, which decide the algorithm's stability.

Numerical error due to grid dispersion can be minimized by ensuring that specific grid cell dimensions are chosen such that they are smaller than the minimum wavelength λ simulated on the grid. A general rule of thumb is to use between 10-20 grid cells per minimum wavelength, meaning that simulated spatial increments should be chosen to be no greater than $\lambda/10$ or $\lambda/20$, respectively. Although this rule does not completely eliminate dispersive effects, it does ensure a smooth variation of the field components across grid cells.

Another important issue faced when explicitly solving the finite-difference form of Maxwell's equations on a grid involves the maximum time-step over which the resulting update expressions can be solved. This upper limit on the time-step results from both the temporal and spatial discretization required for the finite-difference solution of partial differential equations. This inherent stability limit, known as the Courant criterion (Courant *et al.*, 1967), limits the maximum time-step based upon the chosen spatial increments and maximum wave velocity simulated. In 3D, this condition is expressed as:

$$c\Delta t \leq \sqrt{\left(\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} + \frac{1}{(\Delta z)^2}\right)} \quad (28)$$

This is the relationship between the time step and spatial step. When $\Delta x = \Delta y = \Delta z = \delta$,

from Equation (28), $c\Delta t \leq \delta / \sqrt{3} \leq \delta / 2$. That means the wave can propagate the distance of half cell in one time step.

ABSORPTION BOUNDARY CONDITIONS (ABCs)

There have been many attempts over the last several decades to achieve effective ABCs for electromagnetic wave problems. As a result, many different types of ABCs have been developed over the years including the radiating boundary (Holland, 1971), the one-way approximation of the wave equation (Engquist & Majda, 1977), which was later applied to electromagnetic wave problems by Mur (Mur, 1981). Berenger (Berenger, 1996; Berenger, 1997; Berenger, 2002) introduce an alternative way as Perfectly Matched Layer (PML) to truncate the computational domain for FDTD.

This approach utilizes an absorbing outer boundary layer with a specially designed matching medium to absorb and attenuate propagating electromagnetic waves. The original formulation of this technique involves a numerical field-splitting technique within the boundary layer resulting in an artificial or imaginary layer of cells that can theoretically absorb any kind of traveling wave at any frequency, regardless of the direction of wave travel, and without reflection. By properly selecting the appropriate loss parameters for a dispersionless media, Berenger was able to design an interface between the computational space and the PML that is perfectly matched. Thus, the use of the PML at the boundary of an FDTD grid allows for the physical propagation of waves out towards infinity while effectively reducing the negative and unwanted effect of reflections back into the computational space.

Implementation of the PML is a conceptually straight forward task that requires a reformulation of the conventional FDTD update equations

previously discussed. To include the PML boundary condition into the FDTD algorithm, the field updates in (13) through (18) are expressed in a split-field notation which expands them into a set of twelve new update equations:

$$\begin{aligned}\varepsilon \frac{\partial E_{xy}}{\partial t} + \sigma_y E_{xy} &= \frac{\partial (H_{zx} + H_{zy})}{\partial y}, \\ \mu \frac{\partial H_{xy}}{\partial t} + \sigma_y^* H_{xy} &= -\frac{\partial (E_{zx} + E_{zy})}{\partial y}\end{aligned}\quad (29)$$

$$\begin{aligned}\varepsilon \frac{\partial E_{xz}}{\partial t} + \sigma_z E_{xz} &= -\frac{\partial (H_{yz} + H_{yx})}{\partial z}, \\ \mu \frac{\partial H_{xz}}{\partial t} + \sigma_z^* H_{xz} &= \frac{\partial (E_{yz} + E_{yx})}{\partial z}\end{aligned}\quad (30)$$

$$\begin{aligned}\varepsilon \frac{\partial E_{yz}}{\partial t} + \sigma_z E_{yz} &= \frac{\partial (H_{xy} + H_{xz})}{\partial z}, \\ \mu \frac{\partial H_{yz}}{\partial t} + \sigma_z^* H_{yz} &= -\frac{\partial (E_{xy} + E_{xz})}{\partial z}\end{aligned}\quad (31)$$

$$\begin{aligned}\varepsilon \frac{\partial E_{yx}}{\partial t} + \sigma_x E_{yx} &= -\frac{\partial (H_{zx} + H_{zy})}{\partial x}, \\ \mu \frac{\partial H_{yx}}{\partial t} + \sigma_x^* H_{yx} &= \frac{\partial (E_{zx} + E_{zy})}{\partial x}\end{aligned}\quad (32)$$

$$\begin{aligned}\varepsilon \frac{\partial E_{zx}}{\partial t} + \sigma_x E_{zx} &= \frac{\partial (H_{yz} + H_{yx})}{\partial x}, \\ \mu \frac{\partial H_{zx}}{\partial t} + \sigma_x^* H_{zx} &= -\frac{\partial (E_{yz} + E_{yx})}{\partial x}\end{aligned}\quad (33)$$

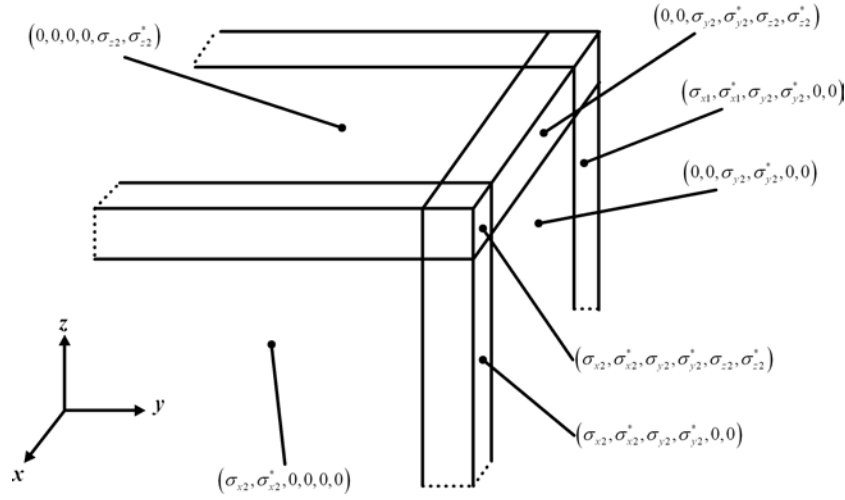
$$\begin{aligned}\varepsilon \frac{\partial E_{zy}}{\partial t} + \sigma_y E_{zy} &= -\frac{\partial (H_{xy} + H_{xz})}{\partial y}, \\ \mu \frac{\partial H_{zy}}{\partial t} + \sigma_y^* H_{zy} &= \frac{\partial (E_{xy} + E_{xz})}{\partial y}\end{aligned}\quad (34)$$

in which each field component has now been split into a summation of two terms (e.g. $E_x = E_{xy} + E_{xz}$) and $\sigma_x, \sigma_y, \sigma_z, \sigma_x^*, \sigma_y^*,$ and σ_z^* represent the corresponding electric and magnetic (*) loss parameters (i.e. conductivities) within the boundary layers. Note here that, if $\sigma_x = \sigma_y = \sigma_z = 0$ and $\sigma_x^* = \sigma_y^* = \sigma_z^* = 0$, then (29) through (34) simply reduce down to (13) through (18), the form of Maxwell's equations appropriate in a vacuum. As waves travel outward and into the PML layer, these conductivities (which can be either linear or polynomial graded) effectively attenuate the wave amplitude absorbing its energy into this unphysical artificial layer. The outermost layer of grid cells is defined as a perfect electric conductor (PEC) by setting the tangential components of the electric field to zero and reflect any remaining waves backwards through the PML layer further absorbing any remaining waveforms.

Within the PML absorbing layers there are twelve components of the electric and magnetic fields that must be updated at each time-step. Figure 2 illustrates the implementation of a conventional PML layer surrounding a 3D computational space. The subscripting in the figure is included for the most general case in which the specific PML layer thickness at each boundary are arbitrary. In other words, the front face (i.e. front yz plane) might compose of a certain number of layers while the back face may contain a completely different number of total layers. Thus, the specific component conductivities in each of these regions can be completely unique and is accounted for via the integer subscripting in the coordinates given in the figure.

The efficiency of this technique lies in the fact that the FDTD grid itself is virtually unchanged within the main computational space. The only change comes from the additional six field components now required within the split-field PML layers. Within the inner simulation domain, the fields are still updated according to (29) through (34). In the PML, regions, however, the fields are updated using the finite-difference form (29) through (34).

Figure 2. Implementation of PML surrounding 3D computational domain



Immediately following the introduction of the PML method, numerous publications quickly appeared in the literature validating this new approach and reporting on its application directly within FDTD codes and simulations (Taflove & Hagness, 2000). However, it was found that this technique suffered from large reflection errors when trying to absorb low frequency evanescent waves. This could occur if the PML was placed relatively close to the corners or edges of a metallic boundary in the simulation. Second, it was also discovered that large spurious errors could be generated for the case of traveling waves striking a PML boundary at grazing angles near zero incidence. This effect was problematic primarily when the PML was used to terminate highly elongated structures and/or their surrounding domains (Berenger, 1996; Berenger, 1997; Berenger, 1998).

CONVOLUTIONAL PERFECTLY MATCHED LAYER

The convolutional perfectly matched layer (CPML), was introduced by Roden and Gedney (Roden & Gedney, 2000) in 2000 and was based upon the previously published complex frequency-

shifted PML (CFS-PML) parameters originally introduced by Kuzuoglu and Mittra (Kuzuoglu & Mittra, 1996) in 1996 and later implemented by Gedney (Taflove & Hagness, 2005) and Tong *et al.* (Tong *et al.*, 1999), based on a stretched-coordinate formulation (Chew & Weedon, 1994) incorporated into a recursive convolution algorithm (Luebbers *et al.*, 1990).

Transforming the Maxwell's equations in the stretched-coordinate space, then we can write the first two Equations (29) and (30) of Berenger's PML in phasor domain as

$$j\omega\epsilon_s \tilde{E}_{xy} = \frac{\partial}{\partial y} (\tilde{H}_{zx} + \tilde{H}_{zy}) \quad (35)$$

$$j\omega\epsilon_s \tilde{E}_{xz} = \frac{\partial}{\partial y} (\tilde{H}_{yx} + \tilde{H}_{yz}) \quad (36)$$

where

$$S_i = \kappa_i + \frac{\sigma_i}{\alpha_i + j\omega\epsilon_0} \quad (37)$$

are the metrics of the stretched-coordinates, where $\kappa_i \geq 1$. The metrics are known as the complex-

frequency shifted (CFS) coordinates. Also the parameters $\sigma_i, \alpha_i \geq 0$ are introduced in the PML region to absorb the outgoing waves. (Note that $\kappa_i = 1$, and $\sigma_i = \alpha_i = 0$ outside the PML regions). The introduction of a non-zero α_i can improve the PML performance at low frequencies, by enhancing the absorption of the evanescent waves. An extra term appears when we substitute the impulse response of s_i^{-1} into (36) and (37) and discretize the update equations. This term can be computed efficiently by using the recursive convolution method. The details of this derivation are omitted here.

The explicit updates are very similar to Equations (19) through (24) except for the addition of the ψ CPML components, and the κ parameters. The equations are given as:

$$H_x \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^{n+\frac{1}{2}} = H_x \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^{n-\frac{1}{2}} + \left(\frac{\Delta t}{\mu_{i,j+\frac{1}{2},k+\frac{1}{2}}} \right) \times \left[\left(\frac{E_y \Big|_{i,j+\frac{1}{2},k+1}^n - E_y \Big|_{i,j+\frac{1}{2},k}^n}{\kappa_{z,k+\frac{1}{2}} \Delta z} \right) - \left(\frac{E_z \Big|_{i,j+1,k+\frac{1}{2}}^n - E_z \Big|_{i,j,k+\frac{1}{2}}^n}{\kappa_{y,j+\frac{1}{2}} \Delta y} \right) \right] + \psi_{H_{x,z}} \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^n - \psi_{H_{x,y}} \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^n \quad (38)$$

$$\psi_{H_{x,z}} \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^n = b_{z,k+\frac{1}{2}} \psi_{H_{x,z}} \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^{n-1} + c_{z,k+\frac{1}{2}} \left(\frac{E_y \Big|_{i,j+\frac{1}{2},k+1}^n - E_y \Big|_{i,j+\frac{1}{2},k}^n}{\Delta z} \right) \quad (39)$$

$$\psi_{H_{x,y}} \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^n = b_{y,j+\frac{1}{2}} \psi_{H_{x,y}} \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^{n-1} + c_{y,j+\frac{1}{2}} \left(\frac{E_z \Big|_{i,j+1,k+\frac{1}{2}}^n - E_z \Big|_{i,j,k+\frac{1}{2}}^n}{\Delta y} \right) \quad (40)$$

$$H_y \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n+\frac{1}{2}} = H_y \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n-\frac{1}{2}} + \left(\frac{\Delta t}{\mu_{i+\frac{1}{2},j,k+\frac{1}{2}}} \right) \times \left[\left(\frac{E_x \Big|_{i+1,j,k+\frac{1}{2}}^n - E_x \Big|_{i,j,k+\frac{1}{2}}^n}{\kappa_{x,i+\frac{1}{2}} \Delta x} \right) - \left(\frac{E_z \Big|_{i+\frac{1}{2},j,k+1}^n - E_z \Big|_{i+\frac{1}{2},j,k}^n}{\kappa_{z,k+\frac{1}{2}} \Delta z} \right) \right] + \psi_{H_{y,x}} \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^n - \psi_{H_{y,z}} \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^n \quad (41)$$

$$\psi_{H_{y,x}} \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^n = b_{x,i+\frac{1}{2}} \psi_{H_{y,x}} \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n-1} + c_{x,i+\frac{1}{2}} \left(\frac{E_z \Big|_{i+1,j,k+\frac{1}{2}}^n - E_z \Big|_{i,j,k+\frac{1}{2}}^n}{\Delta x} \right) \quad (42)$$

$$\psi_{H_{y,z}} \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^n = b_{z,k+\frac{1}{2}} \psi_{H_{y,z}} \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n-1} + c_{z,k+\frac{1}{2}} \left(\frac{E_x \Big|_{i+\frac{1}{2},j,k+1}^n - E_x \Big|_{i+\frac{1}{2},j,k}^n}{\Delta z} \right) \quad (43)$$

$$H_z \Big|_{i+\frac{1}{2},j+\frac{1}{2},k}^{n+\frac{1}{2}} = H_z \Big|_{i+\frac{1}{2},j+\frac{1}{2},k}^{n-\frac{1}{2}} + \left(\frac{\Delta t}{\mu_{i+\frac{1}{2},j+\frac{1}{2},k}} \right) \times \left[\left(\frac{E_x \Big|_{i+\frac{1}{2},j+1,k}^n - E_x \Big|_{i+\frac{1}{2},j,k}^n}{\kappa_{y,j+\frac{1}{2}} \Delta y} \right) - \left(\frac{E_y \Big|_{i+1,j+\frac{1}{2},k}^n - E_y \Big|_{i,j+\frac{1}{2},k}^n}{\kappa_{x,i+\frac{1}{2}} \Delta x} \right) \right] + \psi_{H_{z,y}} \Big|_{i+\frac{1}{2},j+\frac{1}{2},k}^n - \psi_{H_{z,x}} \Big|_{i+\frac{1}{2},j+\frac{1}{2},k}^n \quad (44)$$

$$\psi_{H_{z,y}} \Big|_{i+\frac{1}{2},j+\frac{1}{2},k}^n = b_{y,j+\frac{1}{2}} \psi_{H_{z,y}} \Big|_{i+\frac{1}{2},j+\frac{1}{2},k}^{n-1} + c_{y,j+\frac{1}{2}} \left(\frac{E_x \Big|_{i+\frac{1}{2},j+1,k}^n - E_x \Big|_{i+\frac{1}{2},j,k}^n}{\Delta y} \right) \quad (45)$$

$$\begin{aligned} \psi_{H_{z,x}|_{i+\frac{1}{2},j+\frac{1}{2},k}}^n &= b_{x+\frac{1}{2}} \psi_{H_{z,x}|_{i+\frac{1}{2},j+\frac{1}{2},k}}^{n-1} \\ &+ c_{x+\frac{1}{2}} \left(\frac{E_y|_{i+1,j+\frac{1}{2},k}^n - E_y|_{i,j+\frac{1}{2},k}^n}{\Delta x} \right) \end{aligned} \quad (46)$$

$$\begin{aligned} E_x|_{i+\frac{1}{2},j,k}^{n+1} &= \left(\frac{1 - \frac{\sigma_{i+\frac{1}{2},j,k} \Delta t}{2\varepsilon_{i+\frac{1}{2},j,k}}}{1 + \frac{\sigma_{i+\frac{1}{2},j,k} \Delta t}{2\varepsilon_{i+\frac{1}{2},j,k}}} \right) E_x|_{i+\frac{1}{2},j,k}^n \\ &+ \left(\frac{\frac{\Delta t}{\varepsilon_{i+\frac{1}{2},j,k}}}{1 + \frac{\sigma_{i+\frac{1}{2},j,k} \Delta t}{2\varepsilon_{i+\frac{1}{2},j,k}}} \right) \cdot \\ &\left(\frac{H_z|_{i+\frac{1}{2},j+\frac{1}{2},k}^{n+\frac{1}{2}} - H_z|_{i+\frac{1}{2},j-\frac{1}{2},k}^{n+\frac{1}{2}}}{\kappa_{y_j} \Delta y} - \frac{H_y|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n+\frac{1}{2}} - H_y|_{i+\frac{1}{2},j,k-\frac{1}{2}}^{n+\frac{1}{2}}}{\kappa_{z_j} \Delta z} \right) \\ &+ \psi_{E_{x,y}|_{i+\frac{1}{2},j,k}}^{n+\frac{1}{2}} - \psi_{E_{x,z}|_{i+\frac{1}{2},j,k}}^{n+\frac{1}{2}} \end{aligned} \quad (47)$$

$$\begin{aligned} \psi_{E_{x,y}|_{i+\frac{1}{2},j,k}}^{n+\frac{1}{2}} &= b_{y_j} \psi_{E_{x,y}|_{i+\frac{1}{2},j,k}}^{n-\frac{1}{2}} \\ &+ c_{y_j} \left(\frac{H_z|_{i+\frac{1}{2},j+\frac{1}{2},k}^{n+\frac{1}{2}} - H_z|_{i+\frac{1}{2},j-\frac{1}{2},k}^{n+\frac{1}{2}}}{\Delta y} \right) \end{aligned} \quad (48)$$

$$\begin{aligned} \psi_{E_{x,z}|_{i+\frac{1}{2},j,k}}^{n+\frac{1}{2}} &= b_{z_k} \psi_{E_{x,z}|_{i+\frac{1}{2},j,k}}^{n-\frac{1}{2}} \\ &+ c_{z_k} \left(\frac{H_y|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n+\frac{1}{2}} - H_y|_{i+\frac{1}{2},j,k-\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta z} \right) \end{aligned} \quad (49)$$

$$\begin{aligned} E_y|_{i,j+\frac{1}{2},k}^{n+1} &= \left(\frac{1 - \frac{\sigma_{i,j+\frac{1}{2},k} \Delta t}{2\varepsilon_{i,j+\frac{1}{2},k}}}{1 + \frac{\sigma_{i,j+\frac{1}{2},k} \Delta t}{2\varepsilon_{i,j+\frac{1}{2},k}}} \right) E_y|_{i,j+\frac{1}{2},k}^n \\ &+ \left(\frac{\frac{\Delta t}{\varepsilon_{i,j+\frac{1}{2},k}}}{1 + \frac{\sigma_{i,j+\frac{1}{2},k} \Delta t}{2\varepsilon_{i,j+\frac{1}{2},k}}} \right) \cdot \\ &\left(\frac{H_x|_{i,j+\frac{1}{2},k+\frac{1}{2}}^{n+\frac{1}{2}} - H_x|_{i,j+\frac{1}{2},k-\frac{1}{2}}^{n+\frac{1}{2}}}{\kappa_{z_k} \Delta z} - \frac{H_z|_{i+\frac{1}{2},j+\frac{1}{2},k}^{n+\frac{1}{2}} - H_z|_{i-\frac{1}{2},j+\frac{1}{2},k}^{n+\frac{1}{2}}}{\kappa_{x_i} \Delta x} \right) \\ &+ \psi_{E_{y,z}|_{i,j+\frac{1}{2},k}}^{n+\frac{1}{2}} - \psi_{E_{y,x}|_{i,j+\frac{1}{2},k}}^{n+\frac{1}{2}} \end{aligned} \quad (50)$$

$$\begin{aligned} \psi_{E_{y,z}|_{i,j+\frac{1}{2},k}}^{n+\frac{1}{2}} &= b_{z_k} \psi_{E_{y,z}|_{i,j+\frac{1}{2},k}}^{n-\frac{1}{2}} \\ &+ c_{z_k} \left(\frac{H_x|_{i,j+\frac{1}{2},k+\frac{1}{2}}^{n+\frac{1}{2}} - H_x|_{i,j+\frac{1}{2},k-\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta z} \right) \end{aligned} \quad (51)$$

$$\begin{aligned} \psi_{E_{y,x}|_{i,j+\frac{1}{2},k}}^{n+\frac{1}{2}} &= b_{x_i} \psi_{E_{y,x}|_{i,j+\frac{1}{2},k}}^{n-\frac{1}{2}} \\ &+ c_{x_i} \left(\frac{H_z|_{i+\frac{1}{2},j+\frac{1}{2},k}^{n+\frac{1}{2}} - H_z|_{i-\frac{1}{2},j+\frac{1}{2},k}^{n+\frac{1}{2}}}{\Delta x} \right) \end{aligned} \quad (52)$$

$$\begin{aligned}
 E_z \Big|_{i,j,k+\frac{1}{2}}^{n+1} &= \left(\frac{\sigma_{i,j,k+\frac{1}{2}} \Delta t}{1 - \frac{\sigma_{i,j,k+\frac{1}{2}} \Delta t}{2\varepsilon_{i,j,k+\frac{1}{2}}}} \right) E_z \Big|_{i,j,k+\frac{1}{2}}^n \\
 &+ \left(\frac{\frac{\Delta t}{\varepsilon_{i,j,k+\frac{1}{2}}}}{1 + \frac{\sigma_{i,j,k+\frac{1}{2}} \Delta t}{2\varepsilon_{i,j,k+\frac{1}{2}}}} \right) \cdot \\
 &\left(\frac{H_y \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n+\frac{1}{2}} - H_y \Big|_{i-\frac{1}{2},j,k+\frac{1}{2}}^{n+\frac{1}{2}}}{\kappa_{x_i} \Delta x} - \frac{H_x \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^{n+\frac{1}{2}} - H_x \Big|_{i,j-\frac{1}{2},k+\frac{1}{2}}^{n+\frac{1}{2}}}{\kappa_{y_j} \Delta y} \right) \\
 &+ \psi_{E_{z,x} \Big|_{i,j,k+\frac{1}{2}}^{n+\frac{1}{2}}} - \psi_{E_{z,y} \Big|_{i,j,k+\frac{1}{2}}^{n+\frac{1}{2}}} \Big] \quad (53)
 \end{aligned}$$

$$\begin{aligned}
 \psi_{E_{z,x} \Big|_{i,j,k+\frac{1}{2}}^{n+\frac{1}{2}}} &= b_{x_i} \psi_{E_{z,x} \Big|_{i,j,k+\frac{1}{2}}^{n-\frac{1}{2}}} \\
 &+ c_{x_i} \left(\frac{H_y \Big|_{i+\frac{1}{2},j,k+\frac{1}{2}}^{n+\frac{1}{2}} - H_y \Big|_{i-\frac{1}{2},j,k+\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta x} \right) \quad (54)
 \end{aligned}$$

$$\begin{aligned}
 \psi_{E_{z,y} \Big|_{i,j,k+\frac{1}{2}}^{n+\frac{1}{2}}} &= b_{y_j} \psi_{E_{z,y} \Big|_{i,j,k+\frac{1}{2}}^{n-\frac{1}{2}}} \\
 &+ c_{y_j} \left(\frac{H_x \Big|_{i,j+\frac{1}{2},k+\frac{1}{2}}^{n+\frac{1}{2}} - H_x \Big|_{i,j-\frac{1}{2},k+\frac{1}{2}}^{n+\frac{1}{2}}}{\Delta y} \right) \quad (55)
 \end{aligned}$$

Finally, the CPML parameters α , σ , and κ are one-dimensional (1D) arrays that are each spatially scaled along the x , y , and z axes. They are defined as:

$$\sigma_s(r) = \frac{\sigma_{s,\max} |r - r_0|^m}{d^m} \quad (56)$$

$$\sigma_{s,\max} = \frac{0.8(m+1)}{\eta_0 \Delta s \sqrt{\varepsilon_{r,\text{eff}} \mu_{r,\text{eff}}}} \quad (57)$$

$$\alpha_s(r) = \alpha_{s,\max} \left(\frac{r-1}{d_s} \right)^{ma} \quad (58)$$

$$\kappa_s(r) = 1 + (k_{s,\max} - 1) \left[\frac{|r - r_0|^m}{d^m} \right] \quad (59)$$

where r_0 is the spatial position of each PML/computational space interface, d is the total thickness or physical depth of each PML region, m and ma are the orders of the grading polynomials, $\varepsilon_{r,\text{eff}}$ and $\mu_{r,\text{eff}}$ are the effective relative permittivity and permeability, η_0 is the free-space wave impedance, Δs is the grid cell dimension for $s = x, y$, or z , and $\alpha_{s,\max}$, $\sigma_{s,\max}$, and $\kappa_{s,\max}$ are the maximum assigned values for each of the corresponding 1D arrays. When compared with the traditional split-field PML, the CPML is much easier to implement directly into an existing FDTD algorithm and has demonstrated improved absorption of low-frequency evanescent waves. The CPML can also be easily incorporated into existing FDTD codes already adapted to model anisotropic, dispersive, and nonlinear media. This is a direct result of the way in which the field component updates in the computational space are separated from those in the absorbing boundary layers.

TOTAL-FIELD / SCATTERED-FIELD FORMULATION

The total-field/scattered-field (TF/SF) formulation resulted from attempts to model the source

as a plane wave. Different procedures have been implemented to model the plane wave source condition. The initial attempt to model the incident plane wave condition dates back to Yee's work in 1966 (Yee, 1996) and it was based on a defining the initial condition of the electric field in space. However, this technique requires a large simulation space to model a sinusoidal wave or a long-duration pulse accurately. To overcome this problem, techniques based on the scattered-field (SF) (Holland, 1977) formulation or the total-field/scattered-field (TF/SF) (Mur, 1981; Merewether *et al.*, 1980; Umashankar & Taflove, 1982) formulation have been proposed. Both these techniques are based on the linearity of Maxwell's equations and the possibility to decompose the total E and total H into a known incident and an unknown scattered field. In SF formulation we exploit a new formulation for updating scattered fields, in which the scattered fields in the whole space are updated instead of total fields. However, in the TF/SF formulation, the simulation space is divided into two distinct regions of total field and scattered field which are connected with a hypothetical boundary as shown in Figure 3.

The disadvantage of the SF technique is the need for significant computational resources re-

quired to evaluate the scattered field at any point on or inside the scatterer. However, in this formulation, we exploit the analytical solution of incident field everywhere in space, there are no phase errors due to numerical dispersion such as those that occur on the connecting surface of the original TF/SF formulation (Taflove & Hagness, 2005). However, the advanced formulation introduced in TF/Sf technique has suppressed the numerical dispersion (Watts & Diaz, 2003; Guiffaul & Mahdjoubi, 2000).

THIN-FILM SOLAR CELLS

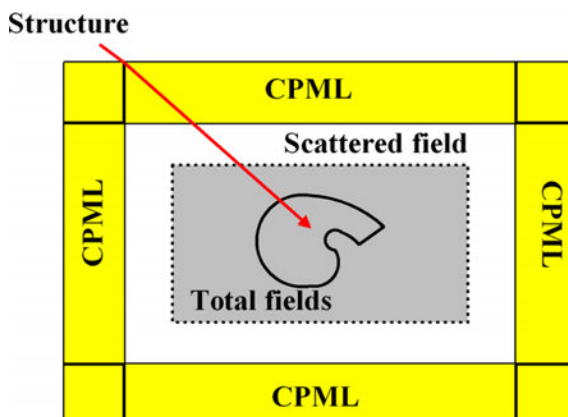
We consider an FDTD modeling example that simulate the electromagnetic wave propagation within the thin-film microcrystalline silicon solar cell. There has recently been considerable interest in applying the FDTD method to the calculation of performance characteristics of solar cells (Dewan & Knipp, 2009; Lin & Phillips, 2008; Lo *et al.*, 2007). Thin-film solar cells are usually produced by physical or chemical deposition techniques, which can be easily applied to large areas and fast throughput (Rech & Wagner, 1999; Meier *et al.*, 2004). Thin-film technology is of much commercial interests because it offers lower costs and possibilities for mass production and deployment.

Light trapping (Zhou & Biswas, 2008) is the standard technique for improving the thin-film solar cell efficiencies and for harvesting the spectrum of incoming sunlight. Enhancing light trapping in thin-film solar cells is typically achieved by a textured metal back reflector that scatters light within the absorber layer and increases the optical path length of solar photons.

SIMULATION OF SOLAR CELL

The geometry of the solar cell is shown in Figure 4 (Dewan & Knipp, 2009). The thickness of the transparent conductive oxide (TCO) front and back

Figure 3. Total-field / scattered-field zones in the FDTD computational space



contacts are considered to be 500 nm and 80 nm respectively. The hydrogenated microcrystalline silicon diode has a thickness of 1000 nm. Further, the silver back layer is modeled as perfectly electric conducting (PEC) wall.

The important factors in the FDTD simulation are dimensions of solar cell layers, permittivity, refractive index, and extinction coefficient (Meng et al., 1993; Wachtman & Haber, 2001; Kaiser & Pulker, 2003). The index of refraction is a complex quantity, $\tilde{n} = n - jk$, where its imaginary part, k , is the extinction coefficient of the material. The permittivity is computed from the complex index of refraction using the formula:

$$\varepsilon_r = n^2 - k^2 \quad (60)$$

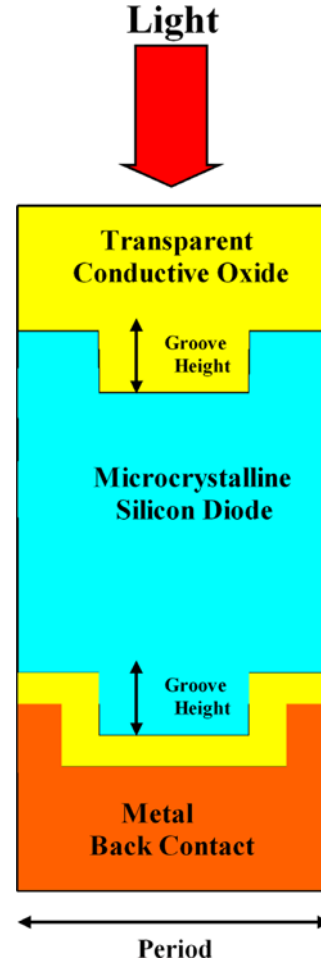
$$\sigma = 2 \cdot n \cdot k \quad (61)$$

The time average power loss $Q(x, y)$ within the solar cell was calculated using the equation (Dewan & Knipp, 2009):

$$Q(x, y) = \frac{c \cdot \varepsilon_0 \cdot n \cdot \alpha}{2} |E(x, y)|^2 \quad (62)$$

where c is the speed of light in vacuum, ε_0 is the permittivity of vacuum, α is the absorption coefficient, with n being the real part of the complex refractive index, and E is the electric field. Figures 5 and 6 exhibit $E(x, y)$ and $Q(x, y)$ for an incident

Figure 4. Solar cell geometry



wavelength of 700 nm with amplitude of 1 V/m. The simulation is performed with the TF/SF technique. Further, the effect of groove height on

Figure 5. Resulted electric field profile for groove heights (a) 100 nm, (b) 200 nm, and (c) 300 nm

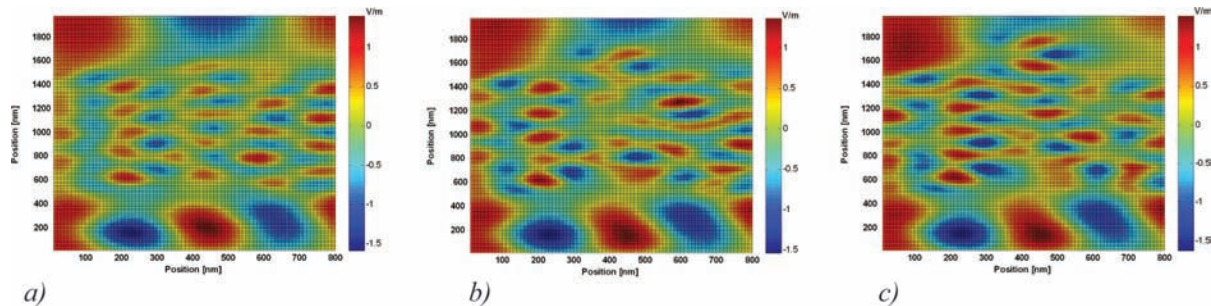
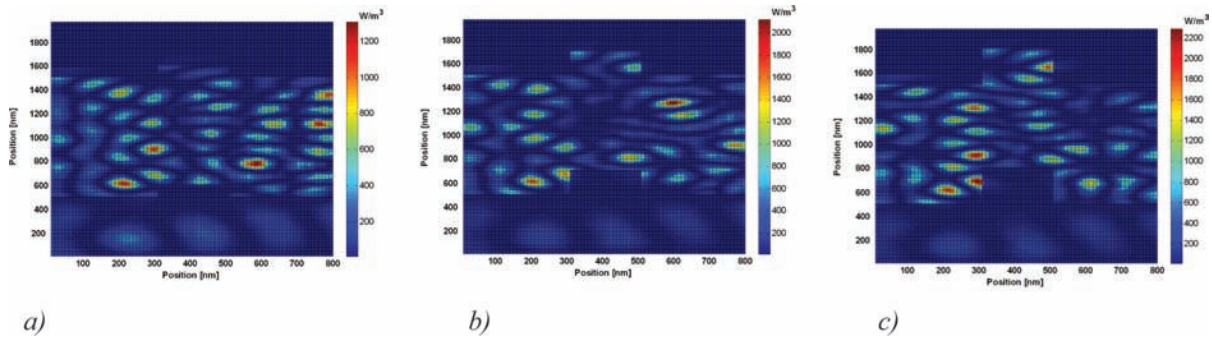


Figure 6. Resulted power loss profile for groove heights (a) 100 nm, (b) 200 nm, and (c) 300 nm



the efficiency of the solar cell is investigated. In the simulation, the groove height of the solar cell was simulated for grooves of 100, 200, and 300 nm, respectively. The result shows that increasing the groove height resulted in more efficient diffraction, and the light absorption increased.

CONCLUSION

Light trapping is the standard technique for improving the thin-film solar cell efficiencies and for harvesting the spectrum of incoming sunlight. Enhancing light trapping in thin-film solar cells is typically achieved by a textured metal back reflector that scatters light within the absorber layer and increases the optical path length of solar photons.

In order to describe the propagation and scattering of sunlight within the solar cell and optimize the process, Maxwell's equations have to be rigorously solved. In this chapter, the development and application of the finite-difference time-domain (FDTD) method to thin-film solar cells is presented.

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KEY TERMS AND DEFINITIONS

Absorbing Boundary Conditions (ABCs): Are artificial absorbing layer for wave equations, commonly used to truncate computational regions in FDTD method to simulate problems with open boundaries.

Courant Criterion: Is a necessary condition for convergence while solving Maxwell's differential equations numerically.

Finite Difference Time Domain (FDTD) Method: Is a powerful tool to solve electromagnetic problems based on the numerical solution of Maxwell's equations.

Nanophotonics: Is the science and engineering of light-matter interactions that take place on wavelength and subwavelength scales where the physical, chemical or structural nature of natural or artificial nanostructured matter controls the interactions.

Perfectly Matched Layer (PML): Is an artificial absorbing layer for wave equations with an absorbing material is that it is designed so that waves incident upon the PML from a non-PML medium do not reflect at the interface.

Solar Cell Efficiency: Is the percentage of electric power converted from incident light.

Thin-Film Solar Cell: Is a solar cell that is made by depositing one or more thin film of photovoltaic material on a substrate.

Total-Field/Scattered-Field (TF/SF) Formulation: Is a method for injecting energy into the FDTD simulation.

Transparent Conductive Oxide (TCO): Is doped metal oxide used in optoelectronic devices such as flat panel display and photovoltaic.

Yee Cell: Is rectangular unit cells of a Cartesian computational grid so that each E-field vector component is located midway between a pair of H-field vector components, and conversely.

Chapter 14

Image Processing for Solar Cell Analysis, Diagnostics and Quality Assurance Inspection

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ABSTRACT

Image capturing, processing, and analysis have numerous uses in solar cell research, device and process development and characterization, process control, and quality assurance and inspection. Solar cell image processing is expanding due to the increasing performance (resolution, sensitivity, spectral range) and low-cost of commercial CCD and infrared cameras. Methods and applications are discussed, with primary focus on monocrystalline and polycrystalline silicon solar cells using visible and infrared (thermography) wavelengths. The most prominent applications relate to mapping of minority carrier lifetime, shunts, and defects in solar cell wafers, in various stages of the manufacturing process. Other applications include measurements of surface texture and reflectivity, surface cleanliness, integrity of metallization lines, uniformity of coatings, and crystallographic texture and grain size. Image processing offers the capability to assess large-areas ($> 100 \text{ cm}^2$) with a non-contact, fast (~ 1 second), and modest cost. The challenge is to quantify and interpret the image data in order to better inform device design, process engineering, and quality control. Many promising solar cell technologies fail in the transition from laboratory to factory due to issues related to scale-up in area and manufacturing throughput. Image analysis provides an effective method to assess areal uniformity, device-to-device reproducibility, and defect densities. More integration of image analysis from research devices to field testing of modules will continue as the photovoltaics industry matures.

INTRODUCTION

This chapter reviews image processing technology and methods in their application to research, engineering development, and production of photovoltaic solar cells. Image processing can be

utilized for device and process diagnostics and materials analysis; as well as for inspection and quality assurance. Most of the foregoing discussion focuses on monocrystalline or multicrystalline silicon solar cells. Such silicon-based solar cells make up about 90% of the world solar cell

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market, and the features and fabrication methods of silicon solar cells readily lend themselves to useful and informative image processing analysis. We will emphasize aspects of image processing with digital photography /machine vision, specifically—analysis of CCD images captured from solar cells in various stages of processing. Many of these techniques are applicable at virtually all phases of solar cell manufacture, including steps preceding the formation of a p - n junction, as well as those preceding application of metal contacts and anti-reflection coatings. More in-depth evaluation is possible with samples that have junctions and metallization contacts, such that the working solar cell can be energized with an externally applied electrical voltage. The resulting infrared thermal emission and electroluminescence can be imaged to provide a two-dimensional map of solar cell characteristics and defects. Images of infrared transmission through the solar cell are also revealing, as the infrared absorption is proportional to the number of free carriers. If free carriers are generated by supra-bandgap excitation, they will quickly reach a steady state concentration where the generation rate is matched by the recombination rate. As such, the density of free carriers is an indicator of the recombination rates, and an infrared transmission image is a map of the variation of minority carrier recombination. Thermography, the temperature mapping of the energized solar cell via thermal infrared emission, is also an important diagnostics tool. Infrared cameras can detect small temperature changes ($< 0.1\text{ }^{\circ}\text{C}$), and image areas of localized heating in solar cells as caused by shunts, for example. Lock-in thermography techniques, using pulsed thermal excitation, for example, flash lamps or modulated lasers or electrical, synchronized with multiple image capture, have increased sensitivities by factors of 100 to 1000.

Imaging techniques can be used to assess surface cleanliness, scratches, reflectivity, surface texture, uniformity of anti-reflection coatings, minority carrier recombination lifetime, localized

shunting, and flaws in metallization. Many of these imaging techniques are relatively fast (~ 1 second), and can be done in-line for real-time process control and quality assurance on the factory floor. More detailed solar cell image analysis methods are realized with scanning/probing techniques, such that small sub-areas of the solar cell are individually probed to show the spatial variation of defects and other areal inhomogeneities. It is important to compare and correlate image processing methods with more established scanning and probing methods since the interpretation and analysis of images is complicated, material- and process-specific, and test conditions (bias, light intensity, minority carrier injection level) may not correspond to actual operating conditions of the solar cell. The solar cell can be scanned by physical contact with a moving mechanical probe that impinges the solar cell, or more commonly, the solar cell can be scanned with a collimated energy source such as a laser or electron beam. Probably the most common and useful of these techniques measures the solar cell current when raster scanned with a laser or focused light beam, in which case it is possible to ascertain highly localized features of the solar cell. This LBIC (light beam induced current) analysis is time consuming and generally not appropriate for in-line inspection. The information derived from light-beam induced current measurements may serve as a benchmark with which methods of simpler or faster solar cell imaging can be compared and assessed.

BACKGROUND

Solar cells are, by practical necessity, large-area devices relative to other semiconductor components. Silicon solar cell areas are typically in the order of 100 cm^2 , and commercial thin-film solar cell modules have areas of hundreds of square centimeters. This may be compared with semiconductor components such as photodiodes and light-emitting diodes (LEDs), where the area of

each discrete semiconductor device (made from die separated from the wafers utilized in batch fabrication) is typically much less than a cm^2 , and often less than a mm^2 . For most semiconductor device technologies, defects and anomalies related to area translate to reduced device yield. A fraction of devices (die) separated from the wafer will fail test since some defects or processing flaws will be localized to individual die. Die that are free of defects will comply with performance specifications. For solar cells, the situation is different: the end-product device generally comprises the entire wafer. A single flaw, such as a shunt defect or a broken busbar metallization line, may necessitate rejection of the entire wafer-based cell. Less-than-fatal flaws will degrade solar cell performance, discounting its value since solar cells are generally sold on a Watts output per dollar basis. Further, the cost consequences of a flawed cell are considerably magnified if assembled as a part of a module. Thus, there is a considerable incentive in identifying and rejecting defective solar cells before their integration into relatively costly module packages.

Due to cost pressures, silicon solar cells are made by processes that would seem relatively crude by the standards of the microelectronics and optoelectronics industry. These processes include screen printing, spray coating, immersion and spray etching, and firing and sintering in conveyor belt furnaces, all done outside clean rooms. Moreover, many solar cells are made from multicrystalline materials that have a variable texture (grain size and orientation). Therefore, it is not surprising that assessment of areal inhomogeneities and variations, and detection of flaws, is a fundamental concern in the production of solar cells. Metzger (2008) made a detailed study based on simulations of photoconductance, carrier density imaging, photoconductive decay, and solar cell performance in silicon material with grain boundaries and lifetime fluctuations on the scale of 5 microns to 5 mm, and concluded the relationships between lifetime measurements, recombination

rates, and performance were sensitive to various parameters (e.g., resolution) of measurement techniques and materials characteristics. This work indicates the complexity and subtleties of predicting solar cell performance in inhomogeneous materials from various characterization methods including imaging.

A solar cell in itself is an excellent diagnostic device: its performance reveals much information about materials properties, device structures, and anomalies in fabrication. However, much of this prospective information follows from an electrical measurement of solar cell current and/or voltage which generally requires a junction and/or electrical contact with the cell. Similarly, other techniques based on electroluminescence, also require contact with the solar cell. To utilize these methods, the solar cell must be in a stage of fabrication where the p - n junction is formed and ohmic contacts have been applied to the device so that the contacts can be connected to an external power supply. To what extent passive (non contact) measurements of the solar cell can provide useful information in comparison to active measurements of an electrically driven solar cell is an important question. Most of the work reviewed here is directed at crystalline and multicrystalline silicon-based solar cells. These types of solar cells comprise a major portion of the world solar cell market, and image processing and analysis efforts have been most developed for this type of solar cell. Many issues resolved by image processing should be common to a wide range of solar cell types. Neuhaus and Menzer (2007) review the dominant silicon solar cell technologies used in industry.

MACHINE VISION FOR SOLAR CELL INSPECTION

What can be learned by “taking a picture” of a solar cell? Specifically, a solar cell in various stages of processing can be imaged with a CCD

camera. (A desktop scanner will also provide workable images.) The lighting—intensity, spectral content, and angle(s) of illumination, often is important., see for example Elango and Kurunamoorthy (2008). Such digital photography can be analyzed with image processing software such as MATLAB® or public domain software such as Image J supported by the US National Inst. of Health (The main application of Image J is for digital microscopy of biological samples.) Some illustrative examples are reviewed below.

Wang *et al.* (2007) used the Image Processing Toolbox of MATLAB® to evaluate the efficacy of silicon wafer cleaning procedures. The software essentially counted contamination particles evident from images of the surface of silicon wafers to assess the effectiveness of laser cleaning methods. They used built-in functions provided for such purposes in the MATLAB® software suite. Commercial surface particle counters (e.g., Particle Guard™, Lighthouse, Inc., San Jose, CA, USA) using video imaging and glancing angle illumination can count and size-range particles (0.5 to 4000 microns) on glass and silicon surfaces on a 4-mm x 6-mm surface in 30 ms.

Contamination of surfaces can also be imaged using ultraviolet light or optically stimulated electron emission (OSEE). OSEE is also an established method of evaluating surfaces for molecular contamination including hydrocarbon and silicone oils, fingerprints, and corrosive solutions at very low levels (Epstein and Schlanger, 2000). A UV light source excites photoelectrons that are collected across an air gap (0.1 to 10 mm) and detected by a voltage-biased probe as a current (10^{-10} to 10^{-12} amps). Contaminants on the surface are detected by the attenuation of the normal signal from the conducting clean surface. Allen *et al.* (2000) describe the use of a commercial scanning OSEE instrument to map the contamination of surfaces. Culik *et al.* (2000) discussed specific application of an OSEE for monitoring and wafer mapping cleaning and etching of silicon solar cell wafers at various processing stages.

Mikhaylichenko and Yakovlev (2003) used fluorescent optical microscopy to identify water stains on wet-cleaned silicon wafers. Water used in cleaning silicon wafers can be spiked with fluorescent dye (10^{-6} g/liter of Rh6G fluorophore) and the surface imaged to show the distribution of water stains on the silicon wafer. Although a simple fluorescence microscope can be used, a confocal microscope will improve resolution by 50%. Using this method, different wafer cleaning and drying methods can be evaluated. In subsequent work, Yakovlev *et al.* (2005) correlated water stains to the surface structure of the wafer.

Measurement of contact wetting angles for drops of liquids placed on the surface of the solar cell can provide a surprising amount of data for a relatively simple effort. Weirauch *et al.* (1993) demonstrated the use of sessile drop technique—measuring the contact angle of a drop on a surface—for evaluating of surface oxidation of HgCdTe. Contact angles and wetting kinetics can be readily measured with a CCD camera (Ritacco 2006). Also, Lokhande *et al.* (2003) measured contact angles of water drops on CuInS₂ films. Drops of ultrapure water (1 to 60 μ l) were placed on the surface-under-test by a vertical syringe, and the profile was imaged with a CCD camera from which the contact angle was measured. Measurement of contact angles with a webcam has been described by Ritacco (2006). Different areas of films showed different contact wetting angles (range 48 to 63°) which corroborated differences shown by scanning electron microscopy, chemical analysis, LBIC, and solar cell performance. Contact angles are a function of surface energies which depends on chemical composition, microstructure, and other factors, which also affect solar cell characteristics. Film areas that exhibited contact angles in the lower range yielded reduced solar cell efficiencies. Accordingly, contact angles could be used to assess the quality of thin films during solar cell fabrication. Angelo *et al.* (2007) used contact wetting angles to characterize CdTe/CdS solar cells in various stages of processing.

The contact angles of water and formamide were used to determine the polar and dispersive surface energies of the component films (ITO indium tin oxide, CdTe, and CdS). For CdTe and ITO, contact wetting angles could be used to measure degree of crystallinity and extent of native oxidation in as-deposited films and in films after annealing in air, argon, CdCl₂, and after surface etching., most of which could be corroborated by other surface analysis methods, such as glancing incidence X-ray diffraction, X-ray photoelectron spectroscopy, and atomic force microscopy, and correlated with solar cell performance.

Fu *et al.* (2004) developed image processing algorithms for inspecting solar cells to detect cracks in solar cells using algorithms such as gray and Gauss-Laplacian transforms for contour detection. The steps are shown in Figure 1. The procedure distinguishes between the more prevalent type of cracks on the edges of the cell and cracks away from edges. Specifically, a JPG color image of a solar cell is transformed to a gray image. On account of the dispersed gray values of the pixels, the gray image is then adjusted, yielding a black and white image of very high contrast. This is followed by a Gauss-Laplacian transform which enhances the signature of cracks. These steps highlight the solar cell edges and any cracks present in the cell. Some lengths of cracks may appear as isolated points due to noise or contaminants (dirt), so the composite points are merged to form a continuous feature. For features (contiguous groups of pixels distinct from the background), a threshold in terms of number of pixels in width and length is used to ascertain a crack. Edge cracks are identified by a search algorithm that starts at a corner of the cell and works around the perimeter of the cell and encountering and noting any putative cracks. Internal cracks are found by an algorithm that scans the interior regions for contiguous pixel groups that fulfill the criteria of a crack. Chiou *et al.* (2011) developed a microcrack inspection system for multicrystalline silicon solar cells using NIR (near infrared) machine vision with a flaw

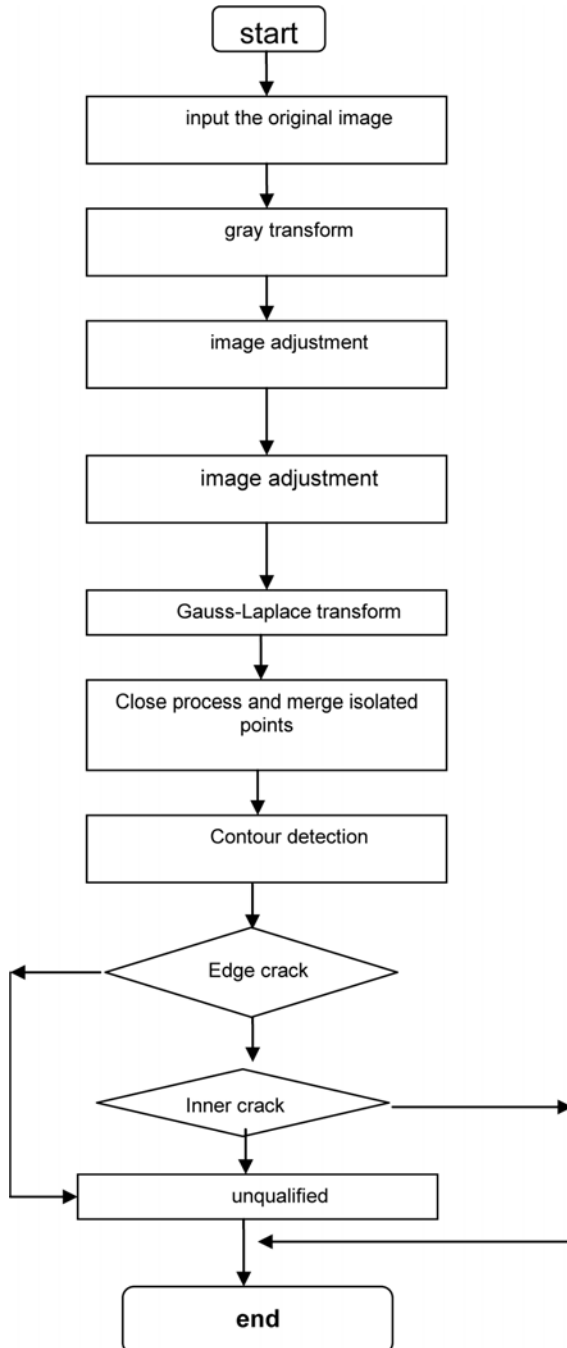
detection algorithm. Jean *et al.* (2011) described an image processing software tool for inspection of silicon solar cells using image processing functions such as average grey level, thresholding, edge detection, template matching, and BLOB (binary large object) analysis.

Sun *et al.* (2010) developed a machine vision system for inspecting electrical contacts. The system acquires the digital image of three views and classifies surface defects including cracks, breaks, and scratches. Although not applied to solar cells, the methodology would appear to be useful in a solar cell and module manufacturing. Chen (2007) has elaborated several image processing methods for solar cell inspection combining multi-case thresholding,

Li *et al.* (2010) described the detection of physical defects in solar cells by a hyperspectral imaging technology. The optical source is a supercontinuum ultra-broadband white-light laser system (Fianium Ltd., Southampton, UK) that produces highly collimated radiation over a 350 to 1400 nm wavelength range. A ‘pushbroom’ imaging system was developed where the light beam (10 W, 50 µm diameter) was scanned in one direction, while the solar cell the solar cell stage is translated in a direction perpendicular to the laser scan direction. The reflected light is collimated and spectrally analyzed with a diffraction grating and CCD camera. An important finding is that the reflections from cracks, grid lines, oily stains, and the featureless areas of the cell all had very distinct and telltale reflection spectrums.

Image-based inspection of multicrystalline wafers is more difficult because the crack shape is similar to the texture, i.e., cracks are difficult to distinguish from grain boundaries, in contrast to cracks in monocrystalline which would tend to be straighter, often along a crystallographic cleavage plane, and therefore show higher contrast against a uniform background. To address this problem, Tsai *et al.* (2010) developed a machine vision scheme based on an anisotropic diffusion model with an adaptive smoothing processing using both gray-

Figure 1. Flow chart for crack inspection of solar cells, from Fu *et al.* (2004)



level and gradients, such that only pixels with both low gray levels and high gradients generate high diffusion coefficients. A more general exposition

of this method is available Chao and Tsai (2010a and 2010b). The application of the anisotropic diffusion image processing scheme to microcrack inspection in multicrystalline solar cells, where the crack must be visible on the the front-illuminated surface of the solar cell, may be summarized as follows. The diffusion process effects a strong smoothing for pixels comprising the putative defect, such that a large diffusion coefficient is assigned to low-gray levels and high gradient magnitudes in gray levels, the diffusion process is arrested for intra-grain regions, and merely a modest smoothing for inter-grain edges (assigned a small diffusion coefficient). As a result, the gray values of pixels comprising the crack are altered, but the gray levels of the crack-free regions are left unchanged. A difference image between the original image and diffused image enhances the crack(s).

SURFACE ROUGHNESS

Silicon wafers used for integrated circuits are mirror-smooth. Solar cells, on the other hand, often incorporate structured, textured, or roughened surfaces. Solar cell performance can be enhanced by texturing (structuring or roughening) the front or back (or both) surfaces of the wafer. This reduces front surface reflection and creates an oblique light path in the solar cell that increases photocarrier generation and short-circuit current. High-efficiency cells rely on such engineered surfaces to achieve the state-of-the-art performance. Silicon wafers can be surface textured by several means including wet chemical etching in acid baths (Ryabova, 2009), and reactive ion etching (Ruby *et al.*, 2005), as well as more sophisticated methods using lithography (Manea *et al.*, 2005). Surface roughness from microfabrication processes can be studied by atomic force microscopy (Chandrasekaran and Sundararajan, 2004), but this contact method is not suitable for in-line inspection. Texturing of single crystal wafers exploits

anisotropic properties of etchants that dissolve crystallographic directions at different rates, leaving a characteristic surface texture. Similar texture etching of multicrystalline wafers is problematic since each grain presents a crystallographically distinct plane at the exposed surfaces of the wafer (Gangopadhy *et al.*, 2005; 2007; Dobrzanski and Drygal, 2008). Thus, it is challenging to formulate an etch that will properly texture each grain. Wet etching baths are notoriously difficult to control, so an image capture station to monitor consistency and yield of a texture etch process should prove useful.

A standard method of surface roughness is surface profiling with a contact stylus that scans the surface and records the amplitude of the surface height, from which an RMS value of surface roughness along one linear direction can be determined. More recently, non-contact interference microscopy can make detailed surface maps of solar cells. While this method is too slow for most in-line measurements, it serves as a 'gold standard' to assess more rapid imaging methods.

There is much relevant work in machine vision for detecting the surface finish of machined metal parts. Luk *et al.* (1989) reported a machine vision system for measurement of surface roughness. A surface illuminated by white light can be characterized by a roughness parameter R , related to the standard deviation SD of pixel intensity and an RMS value defined below. F_i is the number of pixels at grey level X_i (e.g., 0, 1, 2... 255).

$$R = SD / RMS$$

$$SD = \left[\frac{1}{N-1} \sum_{i=0}^{255} F_i \cdot (X_i - \bar{X})^2 \right]^{1/2}$$

$$RMS = \left[\frac{1}{N} \sum_{i=0}^{255} F_i^2 \right]^{1/2}$$

$$\bar{X} = \frac{1}{N} \sum_{i=0}^{255} F_i \cdot X_i$$

$$N = \sum_{i=0}^{255} F_i$$

This roughness parameter correlates well with roughness determined by a surface profilometer. More detailed mathematical descriptions of surface roughness have been presented by Schmahl *et al.* (2006), Jolic *et al.* (1994), Balgunrunathan and Dougherty (2003), Gadelmawla (2004), Kumar *et al.* (2005), and Hu *et al.* (2009), providing a somewhat more elaborate technique for evaluating three-dimensional surface roughness (though not explicitly for solar cells) based on digital image processing. Akbari *et al.* (2006) employed neural networks and image processing for pattern classification of surface roughness. The system is 'trained' with 10 representative samples to learn how to approximate the actual surface roughness with features of the surface image. Al-Kindi *et al.* (2008) validated the used imaging with CCD cameras to assess surface roughness at micro and nano scales.

Elango and Karunamoorthy (2008) used Design of Experiments (DOE) approach to optimize lighting conditions for machine vision determination of surface roughness of machined surfaces. Lighting condition variables of grazing (incidence) angle, light to sample distance, and inclination of striations in sample were varied to optimize the signal-to-noise (S/N) ratio of correlating grey-scale values with surface roughness. Figure 2 shows an experimental set up to parameterize lighting (intensity, color, and angle of illumination) using a ring of LEDs controlled by a computer. Lighting conditions can be varied to better reveal features of the solar cell. The reflection of grains in polycrystalline silicon vary considerably with angle of illumination. For example, Figure 3 shows two views of the same solar cell with different angles of illumination. The left image suggests

the possibility of an interrupted grid line, but the right image indicates the grid line is intact. Inspection of polycrystalline silicon solar cells by image processing may benefit from several image captures with different lighting conditions.

SURFACE ASSESSMENT BY INTERFEROMIC IMAGING

White light interferometric measurements produce an image of surface features at very high resolution. The height variations are in the sub-nanometer range. White light interferometry is based on an optical instrument that combines a reference polychromatic or narrow bandwidth (as produced by an LED) light beam with light reflected from the surface of the sample to generate interference effects representative of the sample surface topography (Haase 2010), as shown in Figure 4. Commercial systems are available (Veeco, Polytec), including scanning instruments that can map larger surface areas. Interferometry is generally too slow for in-line diagnostics, but can serve as a ‘gold standard’ to assess other faster methods of surface imaging and characterization.

Blewett and Novak (2010) studied the effect of surface texture, as quantified by white light interferometry, on solar cell performance. Figure 5 shows various silicon solar cell surface textures from white light interferometry imaging and the correlation with relative solar cell efficiency.

In-line surface topography metrology (enabling stress calculations) is available (Walecki *et al.* 2008). This technology is capable of measuring 2000 solar cells per hour. Commercial of surface metrology equipment from a number of companies has been described. More detailed analysis of the light scattering properties of solar cell surfaces is available (Jäger *et al.* 2010).

IMAGE PROCESSING FOR GRAIN STRUCTURE ANALYSIS

Determination of grain size from images of material specimens, relevant to polycrystalline solar cells, is a well-established metallographic technique. There is commercial software for image analysis to determine grain distribution (Friel *et al.*, 2000). Also, basic processing of solar cell images can be performed with ImageJ software (a public domain, Java-based image processing

Figure 2. Set-up for controlled illumination of solar cell imaging

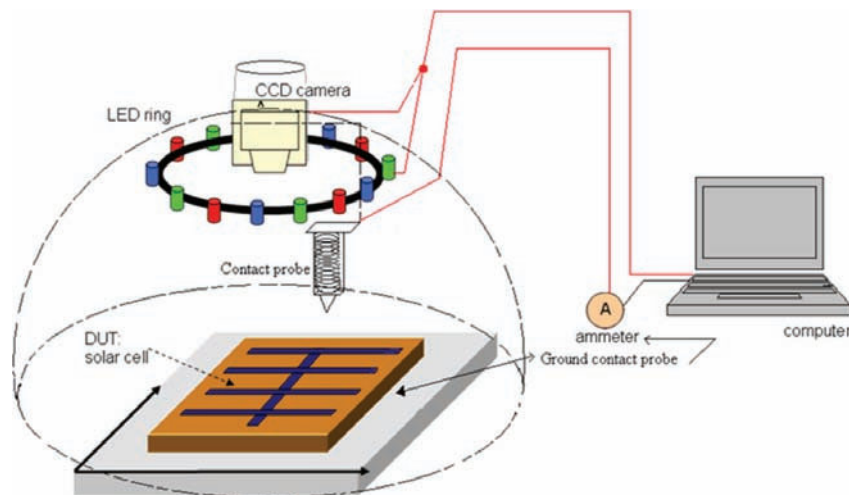
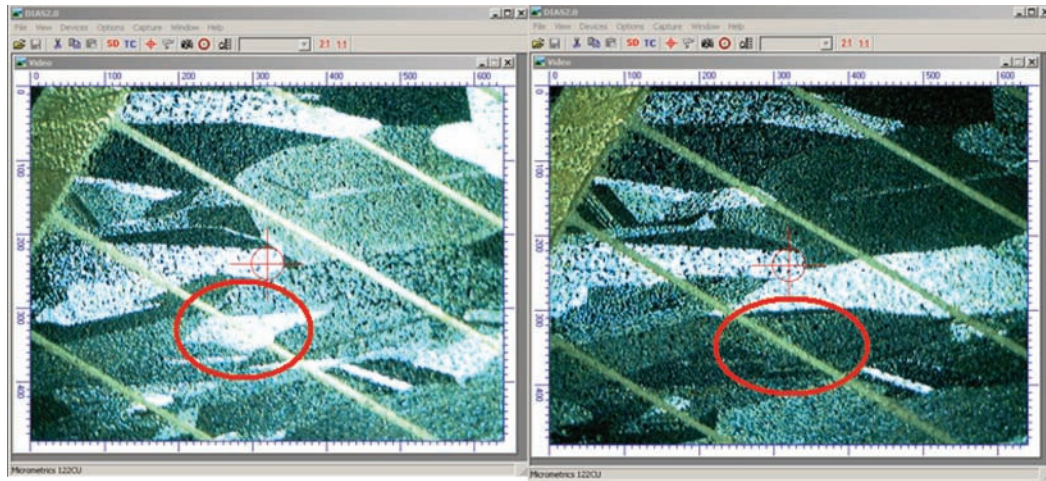


Figure 3. CCD images captured for a polycrystalline silicon solar cell for different angles of illumination



program developed at the National Institutes of Health). ImageJ was designed with an open architecture that provides extensibility via Java plugins and recordable macros.

An early example specific to solar cell work is due to Brenneman *et al.* (1990) who developed a PC-based image analysis that determined grain area and grain boundary length, as well as etch pit densities with features over 0.1 micron or areas larger than 0.01 cm², and inclusions with features 1 micron or larger or areas greater than 0.64 cm². More recently, Forester *et al.* (2009) reported image processing methods to determine

grain size distributions, including discrimination based on identifying subregions with distinct grain morphology, such as small equi-axed grains. A typical application of such work determines how grain structures varies through an ingot of multicrystalline silicon.

Techniques for determining crystallographic orientation from reflection patterns of etched wafers are well known. Wang *et al.* (2010) reported a reflectometry method to determine grain orientations in multicrystalline silicon wafers. The wafer is texture etched with a caustic solution that produces low-index facets and then illuminated

Figure 4. Schematic of white light interferometry imaging system

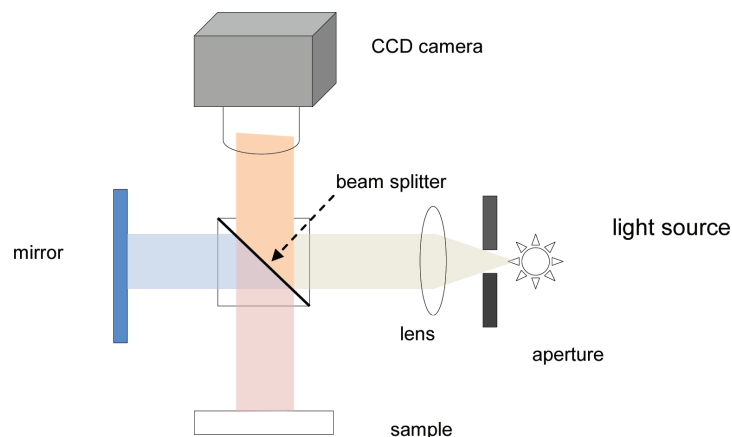
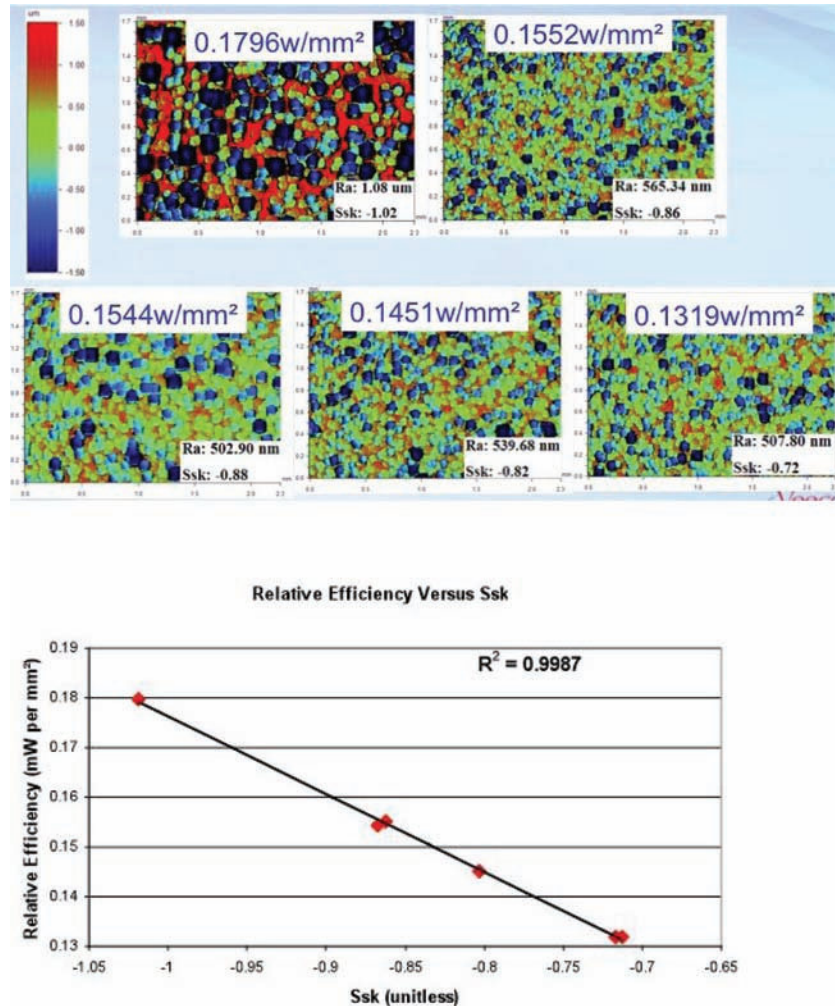


Figure 5. Surface texture differs between cells that exhibit differing efficiency. Several PV cell images with different surface skew (*Ssk*) values are shown here (top). A linear relationship exists between *Ssk* and efficiency for these cells (bottom). (From Blewett and Novak (2010).



at an angle with a laser. A pattern of reflected beams from the wafer is formed on an opaque screen, the characteristic pattern of which can be captured with a CCD camera, and assigned to a particular crystallographic orientation. Thus, the crystallographic index of individual grains can be determined. The laser can then scanned over the wafer to map the orientation of individual grains.

IMAGE ANALYSIS OF COATING UNIFORMITY

The uniformity of anti-reflection coatings (ARCs) can be readily assessed by image processing. Often, this is for purely cosmetic reasons. Non-uniformities in the anti-reflection coating(s), in combination with surface texturing, and specifically areal non-uniformities in the thickness and refractive index of an anti-reflection coating, can adversely affect the performance of the solar cell. Even when performance impact is negligible, the

solar cell may exhibit irregular appearances which derate its commercial value. Sopori *et al.* (2004, 2005) describe a spectral mapping and imaging technology to determine variation in solar cell ARC thickness over the surface of the wafer, as shown in Figure 6.

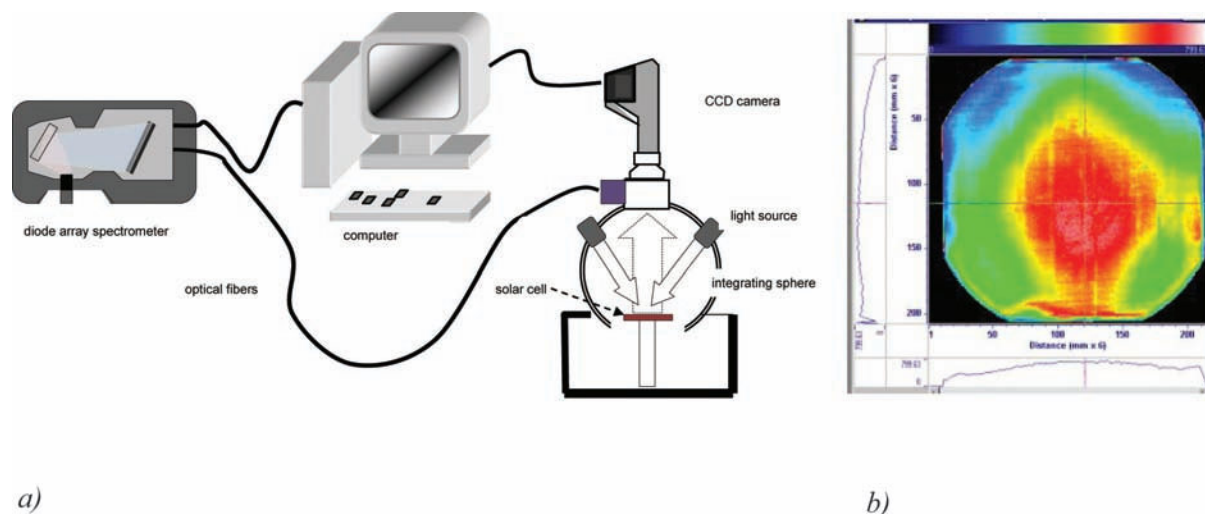
They note that commercial ARCs exhibit variations of ± 10 nm in film thickness, which can lead to losses in photocurrent density of 1 mA/cm², corresponding to a roughly 3% (relative) loss in output power. In the spectral mode, the solar cell is placed in an optical integrating sphere, illuminated with white light, and the reflected light is analyzed with a spectrometer to determine the reflection spectrum, from which thickness and refractive index can be calculated. In a scanning mode, this will produce a map of ARC parameters over the entire wafer. In the imaging mode, a CCD camera with a bandpass filter blocks all light not of interest for the ARC mapping, such that the filtered image represents a local intensity which is inversely proportional to the ARC thickness. This technique can measure a solar cell in less than 40 ms. For in-process solar cell inspection

used to adjudicate thickness (without analysis), simpler cameras and set-ups should suffice.

FEATURE RECOGNITION

Image processing is well suited for feature-recognition, and in particular, the detection of broken busbar and grid fingers. They are well developed algorithms for extracting features, including flaws, from images of products, see for example McAndrew (2004) and Zhao (2005). There is interesting and relevant work done in the area of computer vision for food quality evaluation (Sun, 2008) that could be applied to solar cell production, including image segmentation techniques (Zheng and Sun, 2008), object measurement methods (Zheng and Sun, 2008), object classification methods using fuzzy logic (Zheng, 2008), and hyperspectral methods (Lu, 2008). Medical and biological applications may also provide useful methodologies, see for example, Wootton, Springall, and Polak (1995).

Figure 6. (a) Schematic of setup for spectral and image analysis of silicon solar cell anti-reflection coatings; After Sopori et al. (2004). (b) An anti-reflection coating thickness map for a 4.5-in x 4.5-in silicon solar cell; from Sopori et al. (2004)

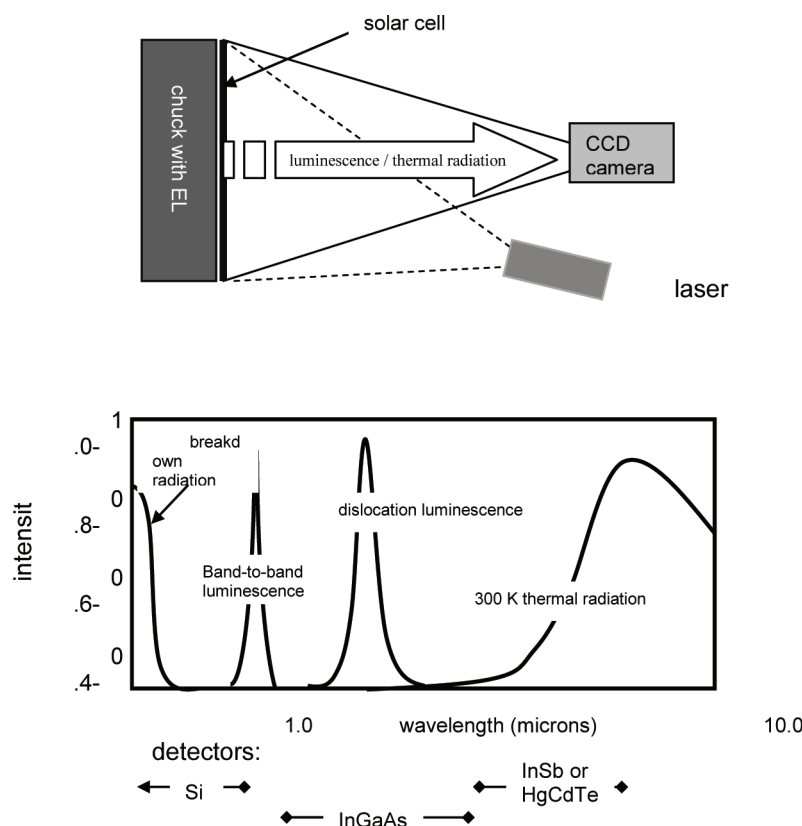


IMAGING METHODS SPECIFIC TO SEMICONDUCTORS AND THE PHOTOVOLTAIC EFFECT

The methods described above are not specific to solar cells, and in fact, most were previously developed for non-solar cell applications. They can be used for inspection of many types of solid parts. Phenomena unique to semiconductors, and electrical injection processes that accompany the photovoltaic effect, provide a wealth of physical effects that can be imaged, including photoluminescence, electroluminescence, variations in carrier density, modifications of reflectivity, and thermal effects. The basis of these effects is that defects and other inhomogenities will cause perturbations in the minority carrier concentration or currents of minority carriers, and indirectly these will be mirrored as variations in luminescence intensity, reflectivity, conductivity, and temperature. For example, localized heating due to a the increased current around a shunt will raise the local temperature around the shunt defect, which can be revealed as an increase in temperature. Imaging techniques can be used to estimate the spatial variation of minority carrier lifetime and diffusion length, and the presence of shunts. In the following, we review four established methods: carrier density imaging, electroluminescence imaging, photoluminescence imaging, thermal imaging, and thermorefectance. The latter two methods depend on spatial temperature variations LBIC (light-beam induced current) mapping and EBIC (electron-beam induced current) mapping have been well reviewed in other venues and, due to their relatively lengthy test time, they are not amenable to the types of in-line inspection that the other methods of imaging can serve. Still, LBIC and EBIC can provide benchmarks to compare the performance of other imaging systems. Warta (2002) discusses the place of imaging methods from the wider perspective of solar cell defect and impurity diagnostics and process monitoring.

Kasemann *et al.* (2008) provide an excellent introductory overview to (silicon) solar cell characterization by infrared imaging methods. These techniques are enabled by advent of fast, low-noise charge coupled devices (CCDs), and mid-IR imagers. Figure 7 shows the basic infrared imaging set-up. Here, a laser (790 to 940 nm wavelength) is used to illuminate the solar cell and create excess photogenerated carriers. Depending on the method, the solar cell can be illuminated either from the front or back side. In some cases, the intrinsic absorption of the solar cell can be used as a filter to attenuate spectral regions that would otherwise interfere with the measurements of interest. The excited solar cell emits radiation, either as narrow luminescence emission due to transitions between discrete bands, or as broader thermal emission at longer wavelengths (as shown in Figure 7). The detector types (Si, InGaAs, InSb or HgCdTe) for the spectral ranges of interest are indicated. Still shorter wavelength radiation is emitted during (reverse bias) junction breakdown. The wavelength-signatures of the radiation allow helps identify the underlying process and defect type. The basic premise is that defects or inhomogenities will locally modify the emission, thus creating image features. Of course, except for a completely homogenous silicon wafer (no grain boundaries) with uniform diffusion, the grids and intrinsic carrier collection patterns in even a ‘perfect’ solar cell will exhibit variations in radiative emission, providing a normal image with typical features. Superimposed on the normal image will be features due to shunts, metallization spiking, electrically active grain boundaries, cluster of dislocations and other defects, and other areal inhomogenities. In thermal imaging methods, these will manifest as hot spots due to temperature variations resulting from the localized heating, for example. An analysis of these anomalies can provide for diagnostics in addition to simple quality control checks. More detailed analysis is possible when the sample (solar cell) temperature and (optical or electrical) injection

Figure 7. Basic principles of luminescence imaging. (a) illumination of solar cell to generate excess carriers, (b) emission mechanisms for relaxation of excited excess carriers in crystalline silicon, and detector types: Si-, InGaAs-, InSb- or HgCdTe-based. After Kasemann *et al.* (2008).



dependence on images enables a carrier lifetime ‘spectroscopy’ (Warta, 2002). Imaging methods based on these luminescence mechanisms are summarized in Table 1.

The excitation for emission can also be achieved by electrical injection, at stages of solar cell processing where a junction and electrical contacts have been formed on the device. True (2010) notes the advantages of photoluminescence include its applicability to finished solar cells or solar cells in process, as no contacts or junction is required, but its disadvantages as an in-line inspection tool include requirements of a pulsed light source and gated detection, critical timing between light source and detection, need for highly uniform illumination and/or non-uniformity correction, poor shot-to-shot reproducibil-

ity. Electroluminescence can use non-gated detectors, with only a simple current source, and exhibits good reproducibility, while its disadvantage is that it can only be applied to near-finished solar cells with a junction and electrical contacts.

Carrier Density Imaging

Carrier density imaging measures the transmission of IR light through the sample, the attenuation of which is proportional to the carrier density. Isenberg *et al.* (2003) used a CCD camera setup for measuring carrier concentration related changes in IR transmission (as shown in Figure 8). The hot plate behind the cell generates infrared radiation. A laser with 917 nm wavelength emission (with silicon absorption length $\alpha^{-1} = 40 \mu\text{m}$) il-

Table 1. Summary of some imaging methods

mechanism	measurands	methods
Band to band Luminescence	Lifetime, diffusion length, interstitial iron, series resistance, shunts	CDI, PLI, ELI
Defect luminescence	dislocations	ELI, PLI
thermal	Hot spots, shunts, series resistance, trapping, emitter sheet resistance, junction breakdown, hot spots, local efficiency	TC-DLIT

CDI carrier density imaging
 PLI photoluminescence imaging
 ELI electroluminescence imaging
 DLIT dark lock-in thermography

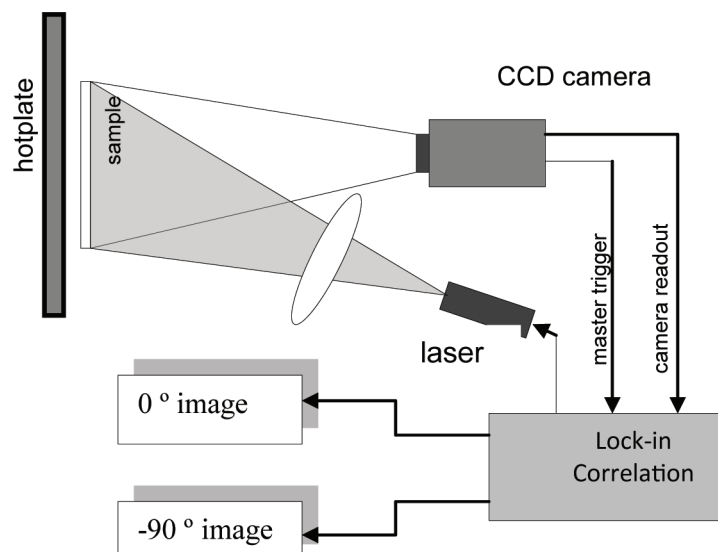
luminesces the cell to generate minority carriers. The resulting free carrier absorption, $\alpha_n \cong 10^{-18} \lambda^2 n$ (for n-type material) and $\alpha_p \cong 10^{-18} \lambda^2 p$ (for p-type material) is effective at the (sub-bandgap) long wavelength thermal radiation from the hot plate. The CCD camera maps the infrared transmission. The lock-in mode mitigates the effects of thermal fluctuations on the hot-plate source. The thermal transmission is first mapped with no laser excitation, and then with laser excitation. The images are then subtracted, and the difference is assumed to be due

to free carrier absorption. The spatially dependent effective minority lifetime $\tau_{eff}(x, y)$ may be inferred from the steady-state balance between carrier generation rate $G(x, y)$, recombination rate $W \cdot \Delta n(x, y) / \tau_{eff}(x, y)$ as:

$$\tau_{eff}(x, y) = \frac{W \cdot \Delta n(x, y)}{G(x, y)}$$

where W is the thickness of the wafer. As the laser illumination is steady, the generation rate can be determined with a control silicon wafer.

Figure 8. Measurement set-up with lock-in thermography for carrier density imaging; after Isenberg et al. (2003)



Accordingly, a map of lifetimes can be deduced. These researchers concluded that CDI is a suitable tool for the measurement of lifetimes on low-time material, as-cut silicon wafers, and wafers after diffusion. It was deemed feasible to reduce the measurement time to less than 1 second with this techniques.

Schubert *et al.* (2006) developed an injection-dependent carrier density imaging method which permits resolution of trapping effects. CDI images are made at different (laser) illumination levels, from which it is feasible to determine injection-level dependent lifetimes. Otherwise, trapping effects can mask actual minority carrier lifetimes. They developed a model where images of low-injection recombination lifetime, trap density, and trapping kinetics could be determined. Schubert *et al.* (2007) noted that rough or textured surfaces have a significant impact on CDI measurements and lead to an overestimation of minority carrier lifetimes. Lifetime values can be corrected by taking emissivity into account through deconvolution and filtering.

Electroluminescence Imaging

In electroluminescence imaging, the solar cell is forward-biased to act as a light-emitting diode (LED). Minority carriers are injected into the base of the solar cell a fraction of which will recombine due to band-to-band transitions which emit a photon. Although silicon is not an efficient source of electroluminescence due to its indirect bandgap, an image can be captured with the cell at room temperature using a Si CCD camera. Defects that introduce mid-gap states will provide an enhanced non-radiative recombination, lowering the amount of radiative recombination. Thus, defective regions of the solar cell will appear as relatively darker areas in the electroluminescence image.

Although silicon is a relatively poor luminescent material (compared to direct bandgap semiconductors such as GaAs), an appreciable EL signal can be detected and it provides diagnostics

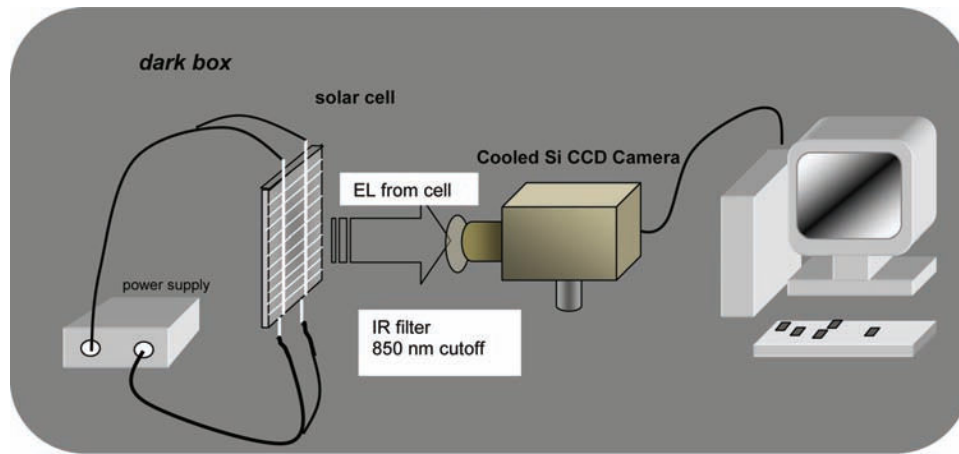
for many types of solar cell defects. Trupke *et al.* (2006) note that state-of-the-art silicon solar cells can exhibit external luminescence quantum efficiencies for the order of 1%, but more typical commercial silicon solar cells show external quantum efficiencies in various stages of processing on the order of 10^{-6} . By comparison, a GaAs LED can achieve external quantum efficiencies approaching 50%.

The basic set up of ELI is shown in Figure 9, after Fuyuki (2003), who developed this technique. The solar cell (with metal contacts and *p-n* junction is forward biased with a current of 1-40 mA/cm². The electroluminescence from the cell is captured with a cooled Si CCD camera.

Trupke *et al.* (2007) described ELI of silicon solar cells in various stages of processing including after caustic etching of the silicon wafer, emitter diffusion, application of a SiN coating, and for fully processed solar cells. Excess minority carriers that recombine at the surface do not contribute to electroluminescence. Temporary surface passivity can be achieved by immersing the wafers in HF or iodine solutions during the ELI measurements. ELI (and photoluminescence imaging) have been used for mapping of diffusion lengths (Fuyuki *et al.*, 2006) series resistance mapping (Trupke *et al.*, 2006a), shunt imaging (Bothe *et al.*, 2006; Trupke *et al.*, 2006; Kasemann *et al.*, 2006), iron imaging (MacDonald *et al.*, 2008), dislocation imaging (Arguirov *et al.*, 2002; Tarasov *et al.*, 2004), and crack detection (Takahashi *et al.*, 2006; Gabor *et al.*, 2006). Figure 10 shows some examples of EL images of commercial monocrystalline and multicrystalline silicon solar cells. The correspondence between SEM, LBIC, and EL imaging for a silicon solar cell sample is indicated in Figure 11.

The above cited work is almost exclusively applied to crystalline silicon solar cells. Brown *et al.* (2010) discuss electroluminescence intensity (though not explicitly EL imaging) as applied to thin-film solar cells. They developed EL intensity equations as a function of materials properties

Figure 9. Experimental set-up for EL imaging; after Fukiyama (2003)



and compared them to EL measurements as a function of both voltage and current, and comparisons with capacitance-voltage, quantum efficiency, and electron-beam induced current, and were able to separate effects of recombination in space-charge regions and quasi-neutral bulk. Several features of thin-film solar cells, such as lateral inhomogeneities and secondary potential barriers, complicate the interpretation of results.

Bothe *et al.* (2009) studied the luminescence of light from commercial multicrystalline silicon solar cells under forward and reverse bias. They observed localized light emission in sub-bandgap 1400 and 1700 nm wavelength region which was attributed to clusters of oxygen.

Photoluminescence Imaging (PLI)

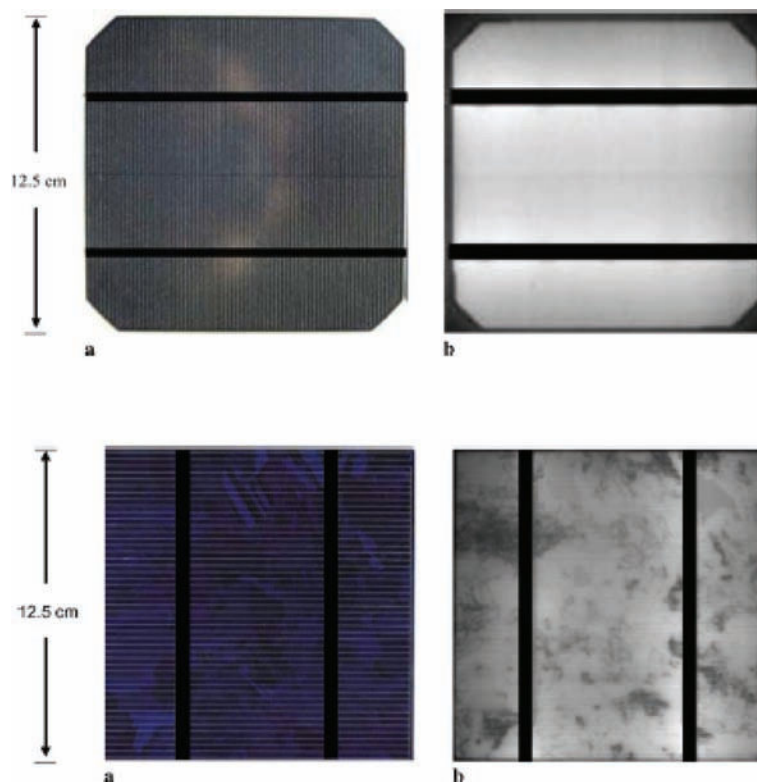
Photoluminescence imaging (PLI) is similar to electroluminescence imaging described above, except that the excess minority carriers are generated by photoexcitation by an external light source rather than electrical injection of a forward-biased *p-n* junction. The main advantage of this non-contact method is that this analysis method can be implemented to wafers before formation of the junction and application of metallization. The basic method and its utility for silicon-based photovol-

taic manufacturing are reviewed by Trupke and McMillan (2010). PL imaging is now routinely used for assessing silicon ingots, wafers, solar cells in various stages of fabrication, and solar modules. They note the experimental challenges for solar cell applications of PL imaging include: a) the requirement for continuous optical power of typically 100 mW/cm² over an area of at least 156-mm x 156-mm, b) the need for homogeneous illumination over that area, and c) the low quantum efficiency of silicon luminescence. Commercial PLI systems (e.g., BT Imaging, Surry Hills, NSW, Australia) for in-line inspection have throughputs of 2400 wafers/hour.

PLI estimates of bulk minority carrier lifetime in silicon ingots prove to be a useful predictor of silicon wafer quality and monitor for process control. Haunschild *et al.* (2010a,b) used PLI on the side faces of silicon 'bricks' (multicrystalline ingots) to rate the quality of the material near the surface. In comparison to the competing technique of microwave photoconductive decay (MW-PCD), PLI proved faster and revealed more details. PL images of wafers cut from an ingot for 'tomographic' information that can be used to optimize the crystallization process.

Trupke *et al.* (2006a,b) reported PLI of silicon wafers as an extremely fast, spatially-resolved

Figure 10. EL imaging of multicrystalline silicon solar cell. a) photograph, and b) EL image; from Fuyuki and Kitiyanan (2009)

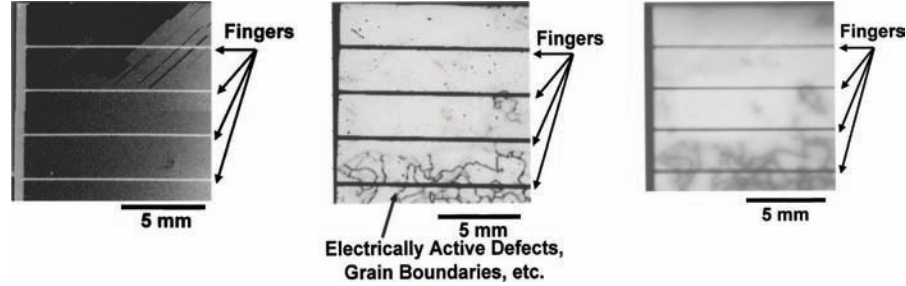


characterization technique that could be applied to large area wafers. A 15-W/ 815-nm diode laser is used to illuminate the samples. Illumination intensity variation across 8.5-cm x 8.5-cm samples was less than 5%. The PLI was captured with a 1-megapixel silicon CCD camera thermoelectrically cooled to -20 °C. Spatial (lateral) resolutions of 130 microns were achieved. A 1000-nm wavelength cutoff long-pass filter blocks the laser illumination from entering the CCD camera. Minority carrier lifetimes ranging from 10 to 160 μ s over a single wafer were typical, and correlated with minority carrier lifetimes resolved by carrier density imaging (CDI). In practical cases, quasi-steady-state photoluminescence imaging (QSS-PLI) is unaffected by depletion region modulation effects, temperature variations due to excitation illumination, or minority carrier trapping. Every

technique for mapping minority carrier properties has implicit assumptions and limitations, and it is sometimes difficult to reconcile different results between different methods. An appealing feature of PLI is that the same technique can be used from ingot to assembled module, and the method can be readily applied before and after a process step is implemented in order to assess the effect of that process on minority carrier recombination. These workers noted that shortly after its introduction with UNSW (University of New South Wales) buried contact solar cells, PLI ‘revolutionized process monitoring and has been used routinely on an almost daily basis for all process and cell development.’

Giesecke *et al.* (2008) described PLI for multicrystalline silicon wafers. Figure 12 shows two alternative experimental set-ups for PL imaging

Figure 11. Comparison (from left to right) of SEM (scanning electron microscope), LBIC (light-beam induced current), and EL image of silicon solar cell; from Fuyuki *et al.* (2006)



using either front side or back side illumination of the solar cell. Backside illumination eliminates the effect of reflected light on the image from the illumination source, and in general, images obtained due to front vs. back illumination should differ due to different optical absorption path lengths for the excitation and emitted light. Due to the small luminescence signal, it was estimated that the long pass filter must attenuate the laser light reflected from the sample by eight order of magnitude.

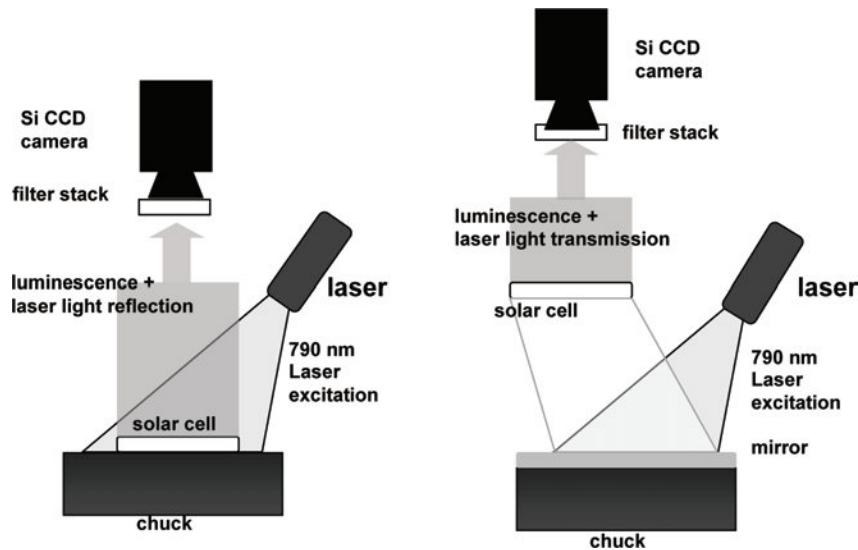
Hinken *et al.* (2009) developed a method for determining the effective diffusion length of

silicon solar cells from a PL measurements under open-circuit (no contact) and short circuit (both contacts grounded). While this technique cannot be considered contactless (due to the grounding of contacts), it does not involve an external driving circuit as does EL measurements.

The photoluminescence intensity I_{PL} is related to excess minority carrier concentration $\overline{\Delta n}$ and effective minority carrier lifetime τ_{eff} as

$$I_{PL} = C \cdot N_{D/A} \frac{1}{W} \int_0^W \Delta n(x) dx = C \cdot N_{D/A} \cdot \overline{\Delta n} \quad (1)$$

Figure 12. Photoluminescence imaging of solar cells: **a.** front-side illumination, **b.** backside illumination; after Giesecke *et al.* (2009)



and

$$\tau_{eff} = \frac{\overline{\Delta n}}{G} \quad (2)$$

where C is a calibration constant (for a fixed illumination, optics, and detection sensitivity), $N_{D/A}$ is the doping, $\overline{\Delta n}$ is the wafer-thickness averaged excess minority carrier, and G is the generation rate (Trupke *et al.*, 2007). Thus, for a set excitation level, the minority carrier lifetime is proportional to the excess carrier concentration, which in turn is proportional to the luminescence intensity.

In general, PLI is fast, contactless, and does not need sample preparation. PLI is relatively immune to carrier trapping effects, especially at low injection levels. The following examples show the versatility of PLI for in situ analysis of solar cell in various stages of processing.

Bardos *et al.* (2006) used PLI to compare similarly-grown n -type and p -type string ribbon multicrystalline silicon at two stages of solar cell processing. They were able to discern that the minority carrier lifetime was significantly lower in p -type material than in n -type material after a light phosphorus diffusion step, and could distinguish good and bad grains along the growth direction. The effects of SiN passivation also differed according to the doping type of the silicon. Sugimoto and Tajima (2007) demonstrated rapid (~ 1 s) characterization of multicrystalline silicon wafers immersed in a HF solution. The HF provides surface passivation to reduce non-radiative surface recombination of minority carriers, resulting in a high photoluminescence signal by two orders of magnitude. Giesecke *et al.* (2009) reported a technique to increase PLI signal from imaging silicon wafers. When detection occurs from the illuminated side of the wafer, the luminescence signal is superimposed with reflected light from the laser excitation. A correction technique based on a separate measure-

ment of reflection topology is used to subtract the effects of the spurious laser reflection. Augarten *et al.* (2009) used photoluminescence imaging for both qualitative and quantitative shunt images. They interpreted luminescence intensity around local shunts in terms of extracted current density, and derived a theoretical relationship between PL signal intensity and shunt current.

$$\frac{PL_{nonshunted} - PL_{shunted}}{PL_{nonshunted}} \cdot \frac{A_{shunted}}{A_{cell}} \cdot I_L = I_{shunt} \quad (3)$$

Thermoreflectance

Thermoreflectance is based on changes in a materials reflectivity with temperature. Thus, variations in temperature over the surface of solar cell will be indicated in a image of the cell reflection. As with other temperature-based techniques, defects and inhomogenities create variations in the current distribution of the cell under bias, and thus are detectable. This thermoreflectance is observed over a wide spectral range, but the effect is relatively small, and so requires sensitive imaging. Kendig *et al.* (2010) used thermoreflectance imaging to identify various defects in amorphous silicon, poly silicon, and CdTe solar cells with a sub-micron resolution. They used megapixel silicon-based CCDs to capture thermoreflectance and electroluminescence signals simultaneously.

THERMOGRAPHIC IMAGING OF SOLAR CELLS

Thermographic imaging is based on the idea that non-uniformities in the areal temperature distribution of a solar cell under light and/or electrical bias provides diagnostic capability for defects and manufacturing variation. By virtue of the electrical contacts and bus bar, the current

distribution in conventional solar cells is inherently non-uniform. Superimposed on this baseline current distribution are current variations due to inhomogenities in series resistance, plus localized regions of material defects and shunting. In multicrystalline material, there are variations in current distribution due to grain boundaries. The current results in Joule heating, and to a lesser extent thermoelectric (Peltier) heating and cooling. Examples consist of a localized shunt region that would exhibit a higher local current, localized heating, and manifest itself as a hot spot of higher temperature than the surrounding area or average temperature of the solar cell surface. An interrupted metallization line would translate to reduced current in that area, and lead to a cooler region of the cell surface. The first task is to thermally image the solar cell with as high as sensitivity (measured in smallest resolved temperature difference ΔT) and spatial resolution as feasible or practical. The thermal imaging can be done under various electrical and optical biases. The second task is to interpret the temperature distribution provided by thermal image(s) in terms of types of defects and manufacturing flaws, with the ultimate aim of eliminating or mitigating these defects. Thermographic imaging has been greatly facilitated and expanded in scope by the development of lock-in thermography (LIT) techniques. In LIT of solar cells, repeated image capture is synchronized to specific phases of a modulated electrical (or sometimes optical) bias which provides the thermal stimulation of the solar cell. These images can be summed or otherwise processed to provide composite images with greatly enhanced signal-to-noise ratios, yielding temperature resolutions in the millikelvin range.

Before reviewing LIT, we mention a few other thermal imaging techniques that have been used for solar cells and other electronic devices. Csendes *et al.* (1996) reported a thermal mapping technique for integrated circuits using liquid crystals. The device under test is coated with a layer of nematic liquid crystal which undergoes a phase transition

at a well-defined temperature which can be viewed with a microscope as the sample is heated. Spatial non-uniformities in temperature are recorded, with a resolution of 0.1 K and 2 to 4 microns. Related techniques were applied to solar cells by Färber *et al.* (1998), Schmidt and Dierking (2001), and Ballif *et al.* (2002). Schmidt and Dierking (2001) covered the solar cell with temperature-sensitive polymer-dispersed cholesteric liquid crystal foils to detect temperature variations in reverse-bias to localize shunts. Correia *et al.* (2004) reported an easy-to-use system for fast shunt analysis using a temperature-controlled stage with vacuum chuck for the solar cells, a liquid crystal foil over the cell and a digital camera that images the temperature-dependent change in reflectivity of the liquid crystal overlayer. They could distinguish between six types of shunts (due to busbar, fingers, scratches, cracks, past contamination, or material defects). A similar technique called fluorescence microthermography (FMT) can be used to locate hot spots in devices and circuits (Herzum *et al.*, 1998). FMT is based on the temperature-dependent luminescence efficiency of rare earth chelate dyes, such as europium theonyltrifluoroacetate (EuTTA) in a PMMA (acrylic) polymer matrix, which are coated on the device under test. The fluorescence emission spectra when excited with UV light is a sensitive function of temperature such that the integrated fluorescence intensity (from about 600 to 630 nm wavelength) around room temperature is

$$I = I_0 \exp(-T / T_0) \quad (4)$$

The intensity temperature relationship can be calibrated with a surface of known temperatures and a CCD camera can image the temperature variation of the solar cell under test. Lateral and thermal resolutions of 0.5 microns and 6 mK were achieved with this method.

Direct thermal imaging with an infrared-sensitive camera is appealing due to its simplicity, ease-

of-interpretation, and potential for in-line process monitoring. Many engineers will be familiar with such qualitative thermal imaging of ‘heat leaks’ in buildings and equipment, and inspecting for ‘hot spots’ in motors and printed circuit boards. Maldague (2001) provides a general exposition of infrared methods for non-destructive testing including thermal emission, heat transfer, IR sensors and optics, imaging and analysis, materials, and experimental methods, for both passive (no heat sourcing probing) and active (response to thermal excitation). Although the relatively low sensitivity of such direct imaging (compared to lock in methods) is limiting in diagnosing many types of defects, there is nevertheless many tasks for which direct thermal imaging is well suited. King *et al.* (2000) surveyed applications of infrared imaging shunts in solar cells (including IR imaging of thin-film solar cells through glass superstrates), resistive solder bonds in solar cell modules, reverse-bias heating in modules, by-pass diode functionality, module temperature distribution, and batteries and other balance-of-system components. Pilla *et al.* (2002) described a thermographic imaging set-up to inspect for cracked solar cells. The solar cell is heated by illumination to about 5 °C over the ambient temperature (which is typical in real applications) and lateral cooling is induced by blowing air on the solar cell and simultaneously monitoring the temperature evolution with an IR camera. This enhances the temperature contrast of cracks, which are enhanced using edge-detection (e.g., Sobel-gradient) image processing algorithms. Avdelidis *et al.* (2011) reported the use of an IR camera (FLIR SC 640, 640 x 40 pixel uncooled microbolometer focal plane array camera with response in the 7.5 to 13 micron wavelength range and sensitivity of 60 mK) to monitor the performance of solar modules in the field. Tsanakas and Botsaris (2011) combined thermal imaging with a transfer analysis of the laminate structure of modules (tedlar, EVA, solar cell, EVA, glass) along with ambient conditions (temperature, humidity, wind speed) to detect and

analyze temperature anomalies in solar modules as a non-destructive evaluation tool performance monitoring. Dunlop and Halton (2004) used a MCT (mercury cadmium telluride) mid-IR camera to thermally image silicon wafers, solar cells and modules that were pulse heated with an electric heating stage or high power xenon flash lamp. They were able to detect cracks, but differentiating between real and apparent temperature differences due to varying emissivity proved problematic in some instances.

Lock-in Thermography

The most powerful method of thermal imaging of solar cells is based on lock-in thermography (LIT). A comprehensive treatment of LIT, not limited to solar cells, can be found in the book by Breitenstein and Langenkamp (2003). In addition to $\phi(x, y) = \phi_{sys}(x, y) + \phi_{sig}(x, y)$ elucidating semiconductor device defects in solar cells, LIT has applications as a non-destructive evaluation (NDE) for modules (Sakagami and Kubo, 2002). Giorelo and Meola (2002) compare conventional pulse thermography and modulated (lock in) thermography in glass-epoxy laminates, the latter technique provides higher spatial resolution and is less perturbed by variations in emissivity and heating. Reviews of lock-in thermography applied to solar cells is provided by Bauer *et al.* (2009), but as applications to solar cells continues to progress the reader should consult the current literature, especially the photovoltaics research conferences. Rotolante and Schneider (2011) provide some useful practical information on set-up and camera specifications for infrared lock-in techniques in solar cell inspection.

The lock-in thermography process is illustrated in Figure 13. A periodic excitation, in the form of electrical bias (e.g., terminal voltage of the solar cell) or optical bias (illumination of the solar cell), or some combination, creates a time- and

spatially varying time-periodic temperature field in the solar cell.

$$T(x, y, t) = A(x, y) \exp[i(\omega t - \phi(x, y))] \quad (5)$$

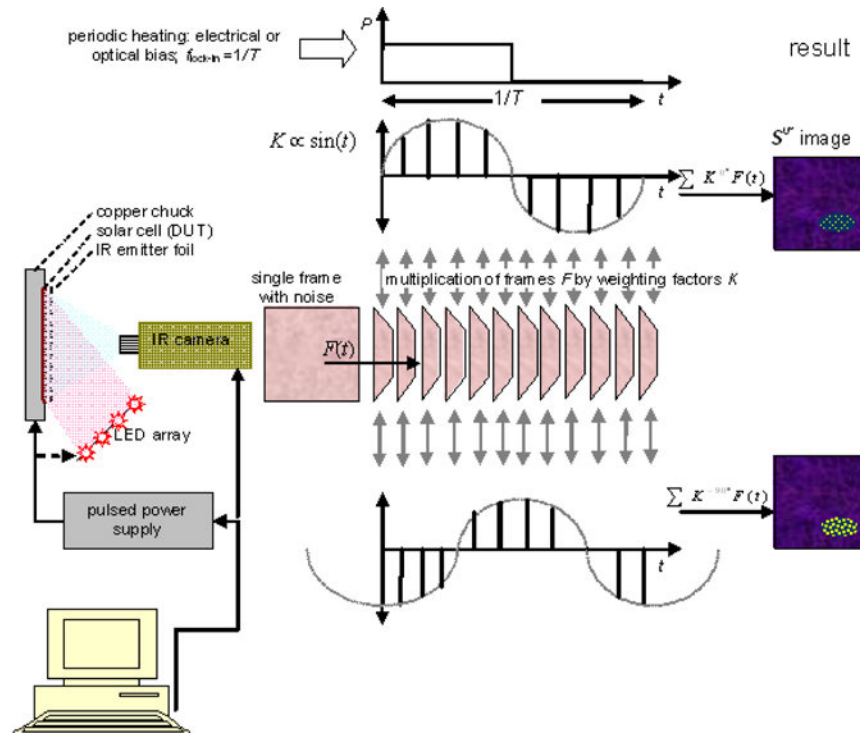
where the phase delay $\phi(x, y)$ is due to both the measurement system and the heat transfer through the solar cell or other device under test (phase delay signal of interest)

$$\phi(x, y) = \phi_{sys} + \phi_{sig} \quad (6)$$

The system phase delay (due to measurement setup) can be determined in a calibration by measuring a homogeneously heated surface where $\phi_{sig} = \pi / 2$ and $\phi(x, y) = \phi_{sys}$. A series of mul-

ti-ple images or frames, at a sampling frame rate f_{fr} , synchronized to the excitation, is taken during each cycle by the camera. Two new sets of images are created: a pair of images from each raw image frame is created by multiplying through two distinct discrete sine and negative cosine weighting factors. These are denoted by K^{0° and K^{-90° because of their phase relationship to the excitation power waveform P , sine as 0° and $-\cos$ as -90° . The second weighting factor (-90°) is called the *quadrature* signal according to its phase relationship with the first weighting factor. Its use rather than $+\cos$ is conventional due to the preference for non-negative results (Gupta and Breitenstein, 2007). This ‘two channel’ processing is required because, in general, the phase delay is

Figure 13. Lock-in thermography system for thermal imaging of solar cells. After Bauer et al. (2009). $F(t)$ represents the 2-D array (x, y) of intensities for each pixel in the image at some discrete image capture time t , for a series of successive image captures. For each image, two new images are calculated using the weighting factors $\sin(t)$, denoted as K^{0° and $-\cos(t)$, denoted as K^{-90° . These are respectively summed to yield images S^{0° and S^{-90° .



not known. These two channels of images are separately summed. The total number summed for each channel depending on how long the device is imaged, and thus how many frames are captured). The longer the imaging time, the higher the signal-to-noise ratio (SNR).

This is the essential reason why high sensitivity can be attained. The noise is uncorrelated to the power waveform and frame rate, whereas the weighted images add 'constructively' during the summation process. The temperature resolution in a single image capture will be limited by the NETD (noise equivalent temperature difference) of the camera (e.g., ~ 5 mK), but integrating multiple image captures ($f_{lock-in} = 20$ Hz; $T = 50$ ms) using the lock-in scheme can achieve sensitivities of 10 microKelvin, which is adequate to detect the localized heating associated with many types of solar cell defects and inhomogenities. The apparent temperature may be different from the actual temperature due to variations in emissivity. This can be corrected by covering the solar cell with a thin black film, or can be factored out as discussed below.

The spatial resolution is fundamentally limited by the wavelength (e.g., 3 to 5 microns) of the infrared light, and also by the spreading of the heat wave which smears out the temperature, an effect which is characterized by the material-specific thermal diffusion length which goes as

$$\frac{1}{\sqrt{f_{lock-in}}} \quad (7)$$

Thus, a fast lock-in rate improves spatial resolution, but this is constrained by the frame rate of the camera. The lock in frequency is related to the camera frame rate

$$f_{lock-in} \leq \frac{f_{fr}}{n} \quad (8)$$

where n is the number of frames captured during the excitation pulse period T . The value of n is typically 10 to 20, and must be greater than 4 according to the Nyquist sampling theorem for a two-channel measurement. Breitenstein *et al.* (2004) discuss other timing schemes for lock-in thermography including undersampling procedures. For imaging with cameras working in the 3-5 micron range, the spatial resolution would be comparable to the wavelength. Breitenstein *et al.* (2006) described silicon-based solid-immersion lenses that improved the spatial resolution of LIT to 1.4 microns, but at close working distances of ~ 1 mm. This is of interest for microelectronic device imaging if not yet most solar cells applications of LIT.

As indicated in Figure 13, the result of the lock-in thermal imaging process is two 2-D image arrays $S^{0^\circ}(x, y)$ and $S^{-90^\circ}(x, y)$, which are related to the amplitude and phase as from which an amplitude image

$$A(x, y) = \sqrt{\left(S^{0^\circ}(x, y)\right)^2 + \left(S^{-90^\circ}(x, y)\right)^2} \quad (9)$$

and a *phase* image

$$\Phi(x, y) = \arctan\left(\frac{-S^{-90^\circ}(x, y)}{S^{0^\circ}(x, y)}\right) \quad (10)$$

can be calculated. $S^{0^\circ}(x, y)$, $S^{-90^\circ}(x, y)$ and $A(x, y)$ are directly proportional to the temperature $T(x, y)$ and can be scaled by calibrating a homogeneous surface of known temperature. $\Phi(x, y)$ is the phase shift between the signal and lock-in reference signal. The amplitude image indicates the heating or strength (magnitude of current) at a local shunt. More particularly, $S^{-90^\circ}(x, y)$ is proportional to the heat dissipated at the shunt and can be used to quantify the extent of shunting. Because the phase image involves the ratio of intensities, it is free of emissivity

contrasts can simplify interpretation of results. Breitenstein *et al* (2004) have suggested still another computed image

$$S^{0^\circ/-90^\circ}(x, y) \equiv \frac{S^{0^\circ}(x, y)}{S^{-90^\circ}(x, y)} \quad (11)$$

which combines the good spatial resolution characteristic of the $S^{0^\circ}(x, y)$ image with the emissivity correction of the $\Phi(x, y)$.

Following Breitenstein *et al.* (2003), a local current-voltage (I - V) characteristic measured thermally, denoted as LIVT, can be related to the amplitude image $A(x, y)$ as

$$LIVT(x, y) = \frac{A(x, y)}{V} \propto I(x, y) \quad (12)$$

where V is the bias voltage. A shunt current I_{shunt} with area $Area_{shunt}$ can be estimated from the $S^{-90^\circ}(x, y)$ image as

$$I_{shunt} = \frac{I_{cell} \times \overline{S_{shunt}^{-90^\circ}}}{\overline{S_{cell}^{-90^\circ}}} \cdot \frac{Area_{shunt}}{Area_{cell}} \quad (13)$$

where the S^{-90° and $Area$ values are referred to the shunt region and the average for entire solar cell. Parameters in a local solar cell dark I - V curve, i.e.,

$$J(V) = J_0(V) \cdot \exp\left[\frac{eV}{n(V)kT}\right] \quad (14)$$

where V is the local bias, $J_0(V)$ is the (voltage-dependent) recombination current, $n(V)$ is the (voltage-dependent) diode ideality factor, k is Boltzmann's constant, and T is the absolute temperature. The voltage dependence of J_0 and n allow for extraction at various bias levels where the dominant diode mechanism may change

(e.g., space charge recombination vs. injection-diffusion)

Measuring the amplitude images at two different bias voltages V_1 and V_2 , the local ideality factor $n(x, y)$ can be estimated as

$$n(x, y) = \frac{e(V_2 - V_1)}{kT \ln \left[\frac{A^{V_2}(x, y) \times V_1}{A^{V_1}(x, y) \times V_2} \right]} \quad (15)$$

Similarly,

$$J_0(x, y) = c \cdot \exp \left[\frac{V_2 \ln \left(\frac{A^{V_1}(x, y)}{V_1} \right) - V_1 \ln \left(\frac{A^{V_2}(x, y)}{V_2} \right)}{V_2 - V_1} \right] \quad (16)$$

where c is found from cell-averaged values as

$$c = \frac{I_2 \times V_2}{\overline{S^{V_2}(x, y)} \times A_{cell}} \quad (17)$$

Below, we review some of the LIT measurement techniques and image analysis methods to diagnose solar cells. The LIT measurements can be done with an optical excitation, electrical excitation, and further, at different points along its I - V characteristic: short-circuit (current), open-circuit (voltage), maximum power point, or reverse-bias. These variations are used according to which solar cell characteristic is sought: series resistance R_s or shunt (parallel) resistance R_p , saturation currents, reverse-saturation currents (J_{01} or J_{02}), ideality factor n , effective minority carrier lifetime τ_{eff} , or various other material defects such as grain boundaries, precipitates, or dislocation clusters. Isenberg *et al.* (2005) has summarized these techniques, as shown in Table 2.

In an early practical solar cell application of LIT, Breitenstein *et al.* (2001) evaluated shunts due to laser scribing and cleaving in silicon cells

using lock-in thermography that could detect temperature variations as low as 10 microKelvin. They were thus able to localize shunting and optimize the laser scribing/cleaving process with respect to avoiding shunt losses.

Kaminski *et al.* (2004) compared LBIC (light-beam induced current) and LIT images of polycrystalline silicon solar cells. In many respects, these techniques provide complementary information about the solar cell. LBIC reveals inhomogenities that reduce short-circuit current, such as areas of high minority carrier recombination, while LIT shows effects that have an impact on open-circuit voltage and fill factor such as ohmic shunts. Ramspeck *et al.* (2007) combined electroluminescence imaging and lock-in thermography to map the recombination current and series resistance of large-area crystalline silicon solar cells. The measured total power loss of the cell was used to scale the DLIT (dark lock-in thermography) image to determine a local heating power density

$$S \rightarrow P_{loc}(x, y) = V_{loc}(x, y) \times J_{loc}(x, y) \quad (18)$$

where $V_{loc}(x, y)$ is the local voltage bias and $J_{loc}(x, y)$ is the local current density.

The electroluminescence image S_{EL} , can be related to the local voltage bias

$V_{loc}(x, y)$ through an equation of the form

$$S_{EL} = \int_z B(t, n, p) \cdot n_i^2(T) \cdot \exp\left[\frac{\Delta\eta(z)}{kT}\right] dz \quad (19)$$

where $B(T, n, p)$ is the radiative recombination coefficient for silicon, n_i is the intrinsic carrier concentration, and $\Delta\eta$ is the splitting of the quasi-Fermi levels, and z is the depth from the front surface. With some assumptions, this leads to

$$V_{loc}(x, y) = \frac{kT}{e} \ln[S_{EL}(x, y)] + c \quad (20)$$

Table 2. Summary LIT methods for solar analysis; after Isenberg *et al.* (2005)

Parameter	Intention	Suggested Method	Comments
J_{01} / τ_{eff}	detect	ILIT @ Voc	J_{01} is the direct measurand
R_p	detect	ILIT or DLIT @ $\approx V_{mpp}$	linear and non-linear shunts detected
	distinguish from J_{0X}	ILIT or DLIT @ $\approx V_{mpp}$	only linear shunts
R_s	detect	ILIT @ JSc or Rs-ILIT @ Jsc/Vmpp	diode currents and bulk recombination
	distinguish from J_{0X}, R_p	Compare ILIT @ Jsc or ILIT @ Voc/Vmpp	several methods of comparison used
J_{02}	detect	ILIT or DLIT @ Vmpp	may be susceptible to non-linear shunts
	distinguish R_p from R_s	See entries for R_p and R_s	
overall power loss		ILIT @ Vmpp	directly proportional to spatial distribution of power losses

Notes: ILIT = illuminated lock-in thermography, DLIT = dark lock in thermography, R_p is the parallel or shunt resistance, R_s is the series resistance, J_{01} are the reverse-saturation dark currents, τ is the effective minority carrier lifetime, Voc = at open-circuit voltage, Vmpp at maximum power point, J_{sc} at short-circuit current.

From which a local series resistance can be determined as

$$R_{loc}(x, y) = \frac{V_{appl} - V_{loc}(x, y)}{J_{rec}(x, y)} \quad (21)$$

where V_{appl} is the external bias applied to the solar cell and which assumes the total local current responsible for heating is equal to the recombination current. Kasemann *et al.* (2006) have made similar analyses combining luminescence imaging and illuminated DLIT.

Most of the work on LIT to solar cells has been directed toward monocrystalline or multicrystalline wafer-based silicon solar cells. Bau *et al.* (2002) used LIT for shunt analysis of epitaxial thin-film silicon solar cells. Straube *et al.* (2011) reported the use of illuminated LIT at different wavelengths for distinguishing shunts in the top and bottom cells of tandem solar cells. Shunting could be identified in tandem solar cells (amorphous silicon on microcrystalline silicon thin films), by performing illuminated (through the glass superstrate, under open-circuit voltage) LIT with white, blue, or infrared excitation, allowing discrimination of shunts in the bottom cell, top cell, or across both cells in series.

Comparisons and Interpretation

Berman *et al.* (2008) evaluated four imaging techniques for electrical characterization of solar cells: photoluminescence imaging, carrier density imaging (CDI), electroluminescence and dark lock-in thermography shunt detection. Photoluminescence imaging and carrier density imaging both generate signals which are proportional to the excess (non-equilibrium) carrier concentration. There is generally good agreement between these methods and LBIC and EBIC studies.

CONCLUSION

Image capture, processing, and analysis provide a remarkable array of tools for solar cell research, diagnostics, and quality control. Virtually every stage of the fabrication process, from grain structure of ingots, cleaning, etching and surface texturing, junction formation, to applications of metallizations and anti-reflection coatings can be productively investigated by image analysis. Unlike most products, the solar cell can be energized by light and/or (at later stages of fabrication) applied voltages that spatially modulate optical, thermal, and electrical properties and phenomena (reflection, luminescence, conductivity) of solar cell structures. A home-made CCD camera image analysis systems can be built for modest cost, and the availability of IR cameras with increasing sensitivity and functionality at lower costs should widen the accessibility of this technology to most researchers. Equipment manufacturers offer an array of sophisticated instruments. Imaging is well-suited for process control, due to its non-contact nature (with the exception of electroluminescence), and high throughput. As might be expected, most of the work to date been directed to wafer-based mono- and multicrystalline silicon solar cells, but the extension of these methods to non-silicon solar cells, thin-film solar cells, and solar cells with nano-scale features appears productive as well.

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Chapter 15

Artificial Intelligence Techniques for Solar Energy and Photovoltaic Applications

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ABSTRACT

Artificial intelligence (AI) techniques play an important role in modeling, analysis, and prediction of the performance and control of renewable energy. The algorithms employed to model, control, or to predict performances of the energy systems are complicated involving differential equations, large computer power, and time requirements. Instead of complex rules and mathematical routines, AI techniques are able to learn the key information patterns within a multidimensional information domain. Design, control, and operation of solar energy systems require long-term series of meteorological data such as solar radiation, temperature, or wind data. Such long-term measurements are often non-existent for most of the interest locations or, wherever they are available, they suffer of a number of shortcomings (e.g. poor quality of data, insufficient long series, etc.). To overcome these problems AI techniques appear to be one of the strongest candidates. The chapter provides an overview of commonly used AI methodologies in solar energy, with a special emphasis on neural networks, fuzzy logic, and genetic algorithms. Selected AI applications to solar energy are outlined in this chapter. In particular, methods using the AI approach for the following applications are discussed: prediction and modeling of solar radiation, seizing, performances, and controls of the solar photovoltaic (PV) systems.

INTRODUCTION, REVIEW OF AI TECHNIQUES

Intelligence is the ability to think, to imagine, create, memorize, understand, recognize patterns, make choices, adapt to change and learn from experience. Artificial intelligence is a human endeavor to create a non-organic machine-based entity that

has all the above abilities of natural organic intelligence. Hence it is known as ‘Artificial Intelligence’ (AI). AI emerged as a computer science discipline in the mid 1950s. Since then, it has produced a number of powerful tools, many of which are of practical use in engineering to solve difficult problems normally requiring human intelligence. Artificial Intelligence (AI) has been defined as the

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study of how to make computers do things which at the moment, people do better (Haugeland, 1985, Rich and Knight, 1991). An Expert System (ES) is a computer program that assimilates and reasons with knowledge obtained from some expert(s) with a view to solving problem(s) or giving advice. Thus expert systems are software packages which translate human expertise into computer programs. Portability of software makes the use of expert systems very attractive where human expertise is scarce or costly or is likely to be lost through mobility. Applications of AI techniques to power and renewable energy systems has been an active area of research for over three decades and significant successes have been achieved. Among the AI techniques, artificial neural networks, fuzzy logic, expert or knowledge based systems have been the most successful.

AI techniques play an important role in modeling, analysis and prediction of the performance and control of renewable energy processes. AI techniques have been used to solve complicated practical problems in various areas of engineering and technology and are become increasingly popular. AI systems can be used as an alternative way to tackle complex and ill-defined problems. They can learn from examples, are fault tolerant in the sense that they are able to handle noisy and/or incomplete data, are able to deal with non-linear problems, and once trained can perform prediction and generalization at high speed. AI systems have been used in diverse applications in control, robotics, pattern recognition, forecasting, power systems, manufacturing, optimization, signal processing, or medical, and social sciences. They are particularly useful in system modeling such as in implementing complex mappings and system identification. AI systems comprise areas like, expert systems, artificial neural networks, data mining, genetic algorithms, fuzzy logic and various hybrid systems, combining two or more techniques. Results presented in various papers, are testimony to the potential of artificial intelligence as a design tool in many areas of energy and

renewable energy engineering. For the modeling, prediction of performance and control of renewable energy processes, analytic computer codes are often used. The algorithms employed are usually complicated involving the solution of complex differential equations, requiring large computer power and need a considerable amount of time to give accurate predictions. Instead of complex rules and mathematical routines, AI systems are able to learn the key information patterns within a multi-dimensional information domain.

The use of the AI techniques in the environmental and renewable energy applications has increased with recognition of its potential. Many of the renewable energy problems are exactly the types of problems, and issues for which AI approach appears to be most applicable. In these models of computation, attempts are made to simulate the cognitive and sensory functions of the human brain and to use this capability to represent and manipulate knowledge in the form of patterns. Based on these patterns, ANNs, for example, model input-output functional relationships and can make predictions about other combinations of unseen inputs. The AI techniques have the potential for making better, quicker and more practical predictions than any of the traditional methods. On the other hand, data from the renewable energy processes, being inherently noisy, are a good candidate to be handled with AI systems. In the following subsections of this chapter short introduction to the AI techniques is presented, as well as their advantages and disadvantages.

ARTIFICIAL NEURAL NETWORKS

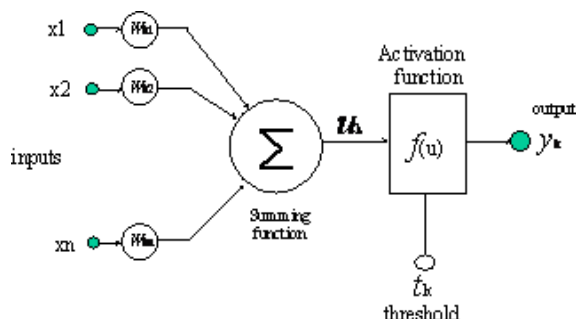
Artificial Neural Networks (ANNs) are information-processing systems inspired by models formulated from the workings of the brain. An ANN consists of interconnected layers of neurons or processing elements. Information is passed between these units along the interconnections. Data is passed through the network from layer to

layer via synapses or connections, each of which is characterised by a weight/strength of its own. In addition an activation function is associated to limit the amplitude of the output of a neuron and is shown in Figure 1. To achieve the desired relationship between the input and output of a network, values must be derived for the connection weights and the activation functions. The process of this derivation is called supervised training. ANNs while implemented on computers are not programmed to perform specific tasks. Instead, they are trained with respect to data sets until they learn patterns used as inputs. Once they are trained, new patterns may be presented to them for prediction or classification. ANNs can automatically learn to recognize patterns in data from real systems or from physical models, computer programs, or other sources. They can handle many inputs and produce answers that are in a form suitable for designers or further processing.

Multi-Layer Perceptron (MLP)

MLPs are perhaps the most common type of feed-forward networks. Figure 2 shows an MLP which has three layers: an input layer, an output layer and a hidden layer. Neurons in input layer only act as buffers for distributing the input signals x to neurons in the hidden layer. An incoming connection has two values associated with it an input and a weight, as shown in Figure 1. The output of the unit is a function of the summed value. The

Figure 1. A simple processing element



processing units in an ANN are interconnected by links (synapses) with weights.

The network has an input layer, an output layer and any number of hidden layers (usually one or two). A neuron is linked to all neurons in the next layer, as shown in Figure 2.

Neuron x has n inputs and one output:

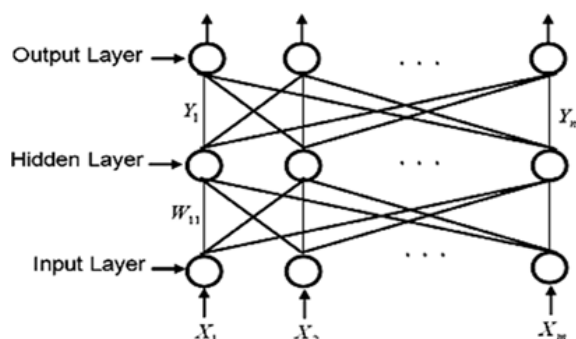
$$y(x) = f\left(\sum_{i=0}^n w_i x_i\right) \quad (1)$$

where $w_0, \dots, w_n$ are the input weights and f is the non-linear activation function (Krishnamoorthy and Rajeev, 1996; Pham and Liu, 1995), usually a step function or a sigmoid. The step function output is $y = 1$ if $x \geq 0$, and 0 otherwise. The sigmoid function, more commonly used, is asymptotic about 0 and 1 and anti-symmetric about (0, 0.5):

$$f(x) = \frac{1}{1 + \exp(-\beta x)} \quad (2)$$

ANNs, while implemented on computer, are not programmed to perform specific tasks. Instead, they are trained with respect to data sets until they learn patterns used as inputs. Once they are trained, new pattern may be presented to them for prediction or classification. ANNs are constructed in layer connects to one or more hidden layers where

Figure 2. An example of an artificial neural network



the factual processing is performance through weighted connections. Each neuron in the hidden layer joins weighted connections. The results of the processing are acquired from the output layer. Learning in ANNs is achieved through particular training algorithms which are expanded in accordance with the learning laws, assumed to simulate the learning mechanisms of biological systems (Belu *et al.*, 2003; Chen *et al.*, 2008). However, as an assembly of neurons, a neural network can learn to perform complex tasks including pattern recognition, system identification, trend prediction and process control (Belu *et al.*, 2003; Chen *et al.*, 2008; Kalogirou, 2001; Kalogirou, 2007). Data are presented to the neural network via input layer, while the output layer holds the response of the network to the input. All hidden and output neurons process their layer input by multiplying each input by its weight (1), summing the products, and then processing the sum via activation (transfer) function to generate a result. Information flow is unidirectional in feed-forward ANNs, with no cycles, but in both directions in feedback ANNs so they have cycles, by which their states evolves to equilibrium (Fuller, 2000; Kalogirou, 2001). In a multi-layer perceptron (MLP), perhaps the most common type of feed-forward networks, input signals are propagated in gradually modified form in the forward direction, finally reaching the output layer.

An important characteristic of the sigmoid activation function (2) that it is differentiable throughout its domain, which makes it suitable for use in the conjunction with a learning algorithm (the weight modification is done in propagation to the negative gradient of the output). The error for hidden layers is determined by propagating back the error determined for the output layer; hence the technique is named back-propagation. During learning, the weights of the neurons are optimised according to the Generalized Delta Rule (GDR), which is the learning algorithm for back-propagation MLP network. The error that is minimized by the GDR is the sum of the squares of the errors for all the output units, defined as:

$$E_p = \sum_k (y_{pk} - o_{pk})^2 \quad (3)$$

For weights' modification of the output layer, the direction in which the weights need to be shifted is determined by the negative gradient of E_p (3) with respect to the weight w_{kj} . The

adjustments in the weight for each neuron is the product of the error in the neuron's output, the gradient of the neuron's output, the net input given to the neuron and a learning rate parameter. The weight's modification in a hidden layer is done in proportion to the gradient of E_p with respect to the hidden layer weights. In this way, each updated weight in a hidden layer is dependent on all the error terms of the output layer. Thus, the errors that could be exactly determined only for the output layer are propagated back to the hidden layers. MLP learning takes place under supervision, and an important parameter that has a controlling effect is the learning rate constant. It decides the magnitude of changes to the connection weights. A high learning rate constant has the advantage of faster learning, but it may cause the weights to bounce around error minima, thus failing to learn properly. On the other hand, if the learning rate constant is too small, the learning may take a long time because of the slow descent along the error surface, which may be favourable as the network may find a better error minimum and, hence, more accurate learning.

Radial Basis Function (RBF)

The RBF network is a type of network that is very useful for pattern classification (Belu *et al.*, 2003; Tefler and Kadambe, 1992). Figure 3 shows the structure of a RBF network consisting of three layers of neurons. The input layer neurons receive the input pattern (x_1 to x_N). The hidden layer neurons provide a set of activation functions that constitute an arbitrary "basis" for the input patterns in the input space to be expanded into the hidden space by the way of nonlinear transformation. At the input of each hidden neuron, the distance between

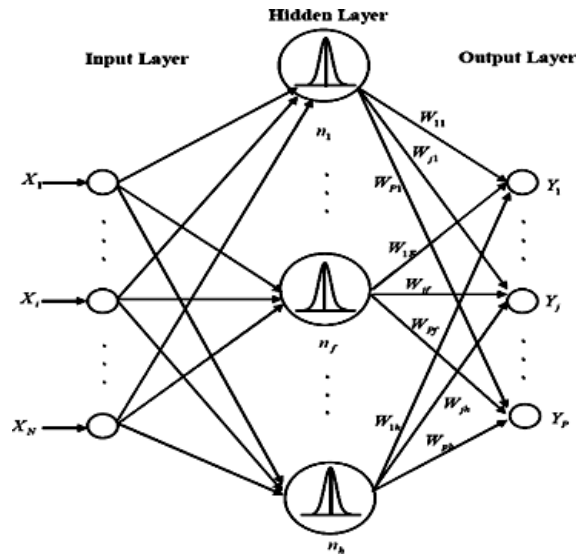
the centre of each activation or basis function and the input vector is calculated. Applying the basis function to this distance produces the output of the hidden neuron. The RBF network outputs y_1 to y_p are formed by the output layer neurons as weighted sums of the hidden layer neuron activations (Chen *et al.*, 2008; Haykin, 1994). The basis function is generally chosen to be a standard function which is positive at its centre $x = 0$, and then decreases uniformly to zero on either side. A common choice is the Gaussian distribution function. The output of the RBF network y_j is given by:

$$y_j = \sum_{i=1}^k w_{ji} K \left(\frac{\|x - c_i\|}{\sigma_i} \right) \quad (4)$$

where w_{ji} is the weight of the hidden neuron i to the output j , c_i is the centre of the basis function i , σ_i is the spread of the function, and $K(x)$ is the activation function.

The purpose of training an RBF network is to determine the neuron weights w_{ji} , RBF centres c_i and spreads σ_i that enable the network to produce the correct outputs y_j corresponding to the input patterns x . The training of an RBF network involves the minimization of an error function. The error function defines the total difference between the actual and desired output of the network over a set of training patterns. Training proceeds by presenting to the network a pattern of known class taken from the training set. The error component associated with that pattern is the sum of the squared differences between the desired and actual outputs of the network corresponding to the presented pattern. The procedure is repeated for all the patterns in the training set and the error components for all the patterns are summed to yield the value of the error function for an RBF network with a given set of basis function centres, spreads and neuron connection weights (Pham *et al.*, 2006).

Figure 3. Topology of an RBF network (adapted from Chen *et al.*, 2008)



FUZZY LOGIC

The concept of Fuzzy Logic (FL) was conceived by Lotfi Zadeh (1965, 1972) a professor at the University of California at Berkley, and presented not as a control methodology, but as a way of processing data by allowing partial set membership rather than crisp set membership or non-membership. This approach to set theory was not applied to control systems until the 70's due to insufficient small-computer capability prior to that time. Professor Zadeh reasoned that people do not require precise, numerical information input, and yet they are capable of highly adaptive control. If feedback controllers could be programmed to accept noisy, imprecise input, they would be much more effective and perhaps easier to implement. In this context, FL is a problem-solving control system methodology that lends itself to implementation in systems ranging from simple, small, embedded micro-controllers to large, networked, multi-channel PC or workstation-based data acquisition and control systems. It can be implemented in hardware, software, or a combination of both. FL provides a simple way to arrive at a

definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input information

Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise. In contrast with “crisp logic”, where binary sets have binary logic, fuzzy logic variables may have a truth value that ranges between 0 and 1 and is not constrained to the two truth values of classic propositional logic (Zadeh, 1965). Furthermore, when linguistic variables are used, these degrees may be managed by specific functions. Fuzzy logic is used mainly in control engineering. It is based on fuzzy logic reasoning which employs linguistic rules in the form of IF-THEN-ELSE statements. Fuzzy logic and fuzzy control feature a relative simplification of a control methodology description. This allows the application of a “human language” to describe the problems and their fuzzy solutions. In many control applications, the model of the system is unknown or the input parameters are highly variable and unstable. In such cases, fuzzy controllers can be applied. These are more robust and cheaper than conventional PID controllers. It is also easier to understand and modify fuzzy controller rules, which not only use human operator’s strategy but, are expressed in natural linguistic terms. FL offers several unique features that make it a particularly good choice for many control problems.

1. It is inherently robust since it does not require precise, noise-free inputs and can be programmed to fail safely if a feedback sensor quits or is destroyed. The output control is a smooth control function despite a wide range of input variations.
2. Since the FL controller processes user-defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter system performance. New sensors can easily be incorporated into the system simply by generating appropriate governing rules.
3. FL is not limited to a few feedback inputs and one or two control outputs, nor is it necessary to measure or compute parameters’ change rate in order to be implemented. Any sensor data that provides some indication of a system’s actions and reactions is sufficient, allowing the use of imprecise and inexpensive sensors thus keeping the overall system cost and complexity low.
4. Because of the rule-based operation, any reasonable number of inputs can be processed and numerous outputs generated, although defining the rule-base quickly becomes complex if too many inputs and outputs are chosen for a single implementation since rules defining their interrelations must also be defined. It would be better to break the control system into smaller chunks and use several smaller FL controllers distributed on the system.
5. FL can control nonlinear systems that would be difficult or impossible to model. This opens doors for control systems that would normally be deemed unfeasible for automation.

Fuzzy systems (FS) use fuzzy sets to deal with imprecise and incomplete data. In conventional set theory an object is a member of a set or not, but fuzzy membership takes any value between 0 and 1. Figure 4 shows the component of a typical fuzzy logic system. Fuzzification transforms exact (crisp) input values into fuzzy membership (Zadeh, 1965, Robert, 1995). Fuzzy models are built on prior rules, combined with fuzzified data by the fuzzy inference machine. The resulting fuzzy output is transformed to a crisp number (defuzzification). Techniques include maximum, mean-of maximum and centroid defuzzification. Figure 3 shows the components of a fuzzy system. The development of fuzzy logic was motivated by the need for a conceptual framework which can address the issue of uncertainty and lexical imprecision. Some of the essential characteristics of fuzzy logic relate to the following (Yager, 1987):

- In fuzzy logic, exact reasoning is viewed as a limiting case of approximate reasoning;
- In fuzzy logic, everything is a matter of degree;
- In fuzzy logic, knowledge is interpreted as a collection of elastic or, equivalently, fuzzy constraint on a collection of variables;
- Inference is viewed as a process of propagation of elastic constraints
- Any logical system can be fuzzified.

There are two main characteristics of fuzzy systems that give them better performance for specific applications:

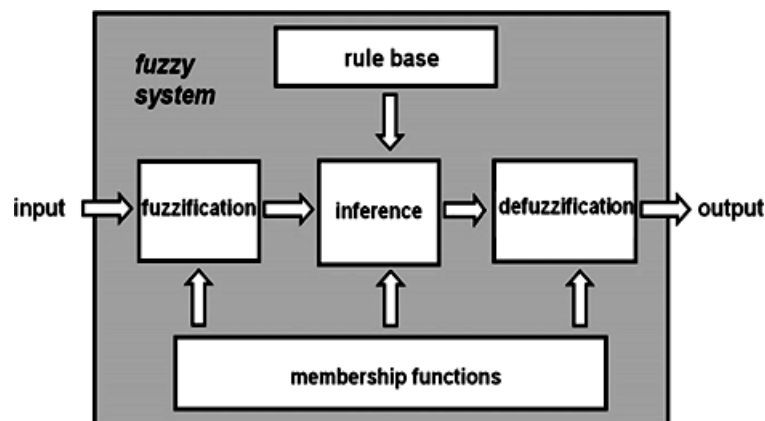
- Fuzzy systems are suitable for uncertain or approximate reasoning, especially for the system with a mathematical model that is difficult to derive
- Fuzzy logic allows decision making with estimated values under incomplete or uncertain information.

The ability of fuzzy logic systems to handle vague or imprecise information represents one of its main strengths over other AI techniques, although they also are easy to understand and apply. One of the main difficulties in developing

a fuzzy system is determining good membership functions. Fuzzy systems have no learning capabilities or memory. To overcome such limitations, fuzzy modeling is often combined with other techniques to form hybrid systems (Lakhmi and Martin, 1998; Von Altrock, 1995; Tefler and Kadambe, 1992). Fuzzy systems handle incomplete or imprecise data in applications including function approximation, classification or clustering, control and prediction. Zadeh (1965, 1972) stated that the attempts to automate various types of activities from assembling hardware to medical diagnosis have been impeded by the gap between the way human beings reason and the way computers are programmed. It attempts to incorporate the “rule of thumb” approach generally used by human beings for decision-making. Thus, fuzzy logic provides an approximate but effective way of describing the behavior of systems that are not easy to describe precisely.

Fuzzy logic controllers, for example, are extensions of the common expert systems that use production rules like “if-then” statements. With fuzzy controllers, however, linguistic variables like “tall” and “very tall” might be incorporated in a traditional expert system. The result is that fuzzy logic can be used in controllers that are capable of making intelligent control decisions in sometimes volatile and rapidly changing problem

Figure 4. The main components of a fuzzy system



environments. Fuzzy logic techniques have been successfully applied in a number of applications like, computer vision, decision-making and system design including ANN training. The most extensive use of fuzzy logic is in the area of control, where examples include controllers for cement kilns, braking systems, elevators, washing machines, hot water heaters, air-conditioners, video cameras, rice cookers and photocopiers. Fuzzy logic has been used for the solar radiation prediction (Mellit *et al.*, 2009) and for the development of a solar tracking mechanism (Kalogirou, 2007).

GENETIC ALGORITHMS

A genetic algorithm (GA) is a stochastic process that mimics the natural process of biological evolution (Harp and Samad, 1991; Buckeles and Petry, 1992). GA's are inspired by the way living organisms are adapted to the harsh environment, i.e. by evolution and inheritance. The algorithms imitate in the process, the evolution of population by selecting only fit individuals for reproduction. Therefore, a GA is an optimum search technique based on the concepts of natural selection and survival of the fittest. It works with a fixed-size population of possible solutions of a problem, called individuals, which are evolving in time. GA's find extensive applications in intelligent search, machine learning and optimization problems. Problem states in a GA are denoted by chromosomes, which are usually represented by binary strings. A GA utilizes three principal genetic operators (Buckeles, 1992; Forest, 1993; Kalogirou, 2007). The initial population $G(0)$ is generated randomly. Thereafter $G(t)$ produces $G(t+1)$ through selection and reproduction (Buckeles, 1992). A proportion of the population is selected to breed and produce new chromosomes, Selection is according to fitness of individual solutions, i.e. proximity to a perfect solution (Forest, 1993), most often by roulette selection and deterministic sampling. Roulette selection randomly selects a

parent with probability computed from the fitness f_i of each individual (Kalogirou, 2007):

$$F_i = \frac{f_i}{\sum_i f_i} \quad (5)$$

Reproduction is by genetic cross over and mutation. Crossover produces offspring by exchanging chromosome segments from two parents. Mutation randomly changes part of one parent's chromosome. This occurs in frequently and introduces new genetic material. Although mutation plays a smaller part than crossover in advancing the search, it is critical in maintaining genetic diversity. If diversity is lost, evolution is retarded or may stop. In steady-state GAs offspring generated by the genetic operators, replace less fitted members, resulting in higher average fitness. Simple or generational algorithms replace each entire generation (Forest, 1993). Selection and reproduction are repeated until a stopping criterion is met, e.g. all organisms are identical or very similar, a given number of evaluations have been completed, or maximum fitness has been reached; evolution no longer yields better results.

GAs are computationally simple and robust, and balance load and efficacy well (Forest, 1993). This partly results from only examining fitness, ignoring other information such as derivatives. Genetic Algorithms treat the model as a black box, an advantage when detailed information is unavailable. An important strength of GAs is implicit parallelism; a much larger number of code sequences are indirectly sampled than are actually tested by the GA. Unlike most stochastic search techniques, which adjust a single solution, GA keeps a population of solutions. Maintaining several possible solutions reduces the probability of reaching a false (local) optimum (Forest, 1993). Therefore GAs can be very useful in searching noisy and multimodal relations. However, the latter may take a large computation time. In most

cases, Genetic Algorithms use randomization in selection. They avoid picking only the best individual and thus prevent the population from converging to that individual. However, premature convergence on a local optimum can occur if the GA magnifies a small sampling error (Forest, 1993). If a very fit individual emerges early and reproduces abundantly, early loss of diversity may lead to convergence on that local optimum. GAs are often used to optimize model parameters or for resource management.

HYBRID SYSTEMS

Hybrid systems combine more than one of the technologies introduced above, either as part of an integrated method of problem solution, or to perform a particular task that is followed by a second technique, which performs some other task. For the modeling, prediction of performance and control of renewable energy processes, analytic computer codes are often used. The algorithms employed are usually complicated involving the solution of complex differential equations. These programs usually require large computer power and need a considerable amount of time to give accurate predictions. Instead of complex rules and mathematical routines, artificial intelligence systems are able to learn the key information patterns within a multi-dimensional information domain. On the other hand, in design, control and operation of renewable energy systems, such as PV or solar-thermal energy systems, a detailed long-term series of meteorological data such as solar radiation, temperature or wind data is normally required. The effort is to design and operate systems that can make an efficient conversion and utilization of these renewable energy resources. However, one of the problems that designers of such systems are often confronted with is the acquisition or availability of sufficiently long series of meteorological variables for direct utilization. Such long-term measurements are often

non-existent for most of the interest locations or, wherever they are available, they suffer of a number of shortcomings (e.g. poor quality of data, missing data, insufficient long series, etc.). To overcome these problems AI techniques appear to be one of the strongest candidates.

The increased popularity of Hybrid Intelligent Systems (HIS) in recent years lies in the extensive success of these systems in many real-world complex problems. The main reason for this success seems to be the synergy derived by the computational intelligent components, such as machine learning, FL, neural networks and GAs. Each of these methodologies provides HS with complementary reasoning and searching methods that allow the use of domain knowledge and empirical data to solve complex problems (Harp and Samand, 1991; Haykin, 1994; Von Altrock, 1995). Hybrid systems combine two or more AI techniques ('paradigm') to gain strengths and overcome weaknesses. HS combining FL, neural networks, GAs, and ES are proving their effectiveness in a wide variety of real-world problems.

There are three main types of hybrid systems according to how the techniques are combined: sequential, auxiliary and embedded (Lakhmi and Martin, 1998). In a sequential hybrid, the first paradigm passes its output to the second to generate the output. In an auxiliary hybrid, the first paradigm obtains some information from the second to generate the output. In an embedded hybrid, the two paradigms are contained in one another (Lakhmi and Martin, 1998). The most common hybrids are neuro-fuzzy systems, combining ANNs and fuzzy systems. They are effective: fast, efficient and easily designed, implemented and understood (Chen *et al.* 2008; Fuller, 2000; Kalogirou 2003). By combining them, the need to prime fuzzy systems is reduced by learning in ANNs. Fuzzy systems attenuate 'noise', from which some ANNs suffer. Each AI technique has capabilities and limitations, making its suitability for environmental modeling specific to that problem. On the other hand, one has to keep in

mid a hybrid system may retain the weaknesses of both techniques and little of their strengths (Kalogirou, 2007; Mellit, 2008). Hybrid techniques also raise the problem of communication; different representations have to be translated into a common language. Another problem of hybrid systems with learning is credit assignment (Tefler and Kadambe, 1992). If one component cannot distinguish changes caused by its own actions from those due to others, penalties and rewards will be ineffective.

Fuzzy Neural Networks

Neural networks can be modified to incorporate fuzzy techniques and produce a neural network with improved performance. One approach is to allow the fuzzy neural network to receive and process fuzzy inputs. Another option is to add layers on the front end of the network to fuzzify crisp input data to the fuzzy neural processing (Fuller, 2000; Tefler and Kadambe, 1992). The fuzzy neuron is a fundamental concept used in many approaches to integrate fuzzy and neural technologies. In networks that map fuzzy input to crisp output, nodes in every layer of the network can have modified neurons. The input consists of a set of fuzzy values, and the weights connecting the node with nodes in the previous layer also have fuzzy values. Input values and the weights are each represented by membership functions. A modified summation process is used to find the product of the membership functions of the fuzzy inputs and weights and then add the resulting membership functions to obtain another one that represents the integration of weighted fuzzy inputs to the node. A centroid operation on the resultant can then be used to find a crisp value for the output of the node. The computational process envisioned for fuzzy neural systems is as follows. It starts with the development of a “fuzzy neuron” based on the understanding of

biological neuronal morphologies, followed by learning mechanisms. This leads to the following three steps in a fuzzy neural computational process (Tefler and Kadambe, 1992):

- Development of fuzzy neural models motivated by biological neurons,
- Models of synaptic connections which incorporate fuzziness into neural network,
- Development of learning algorithms (i.e., the method of adjusting the synaptic weights).

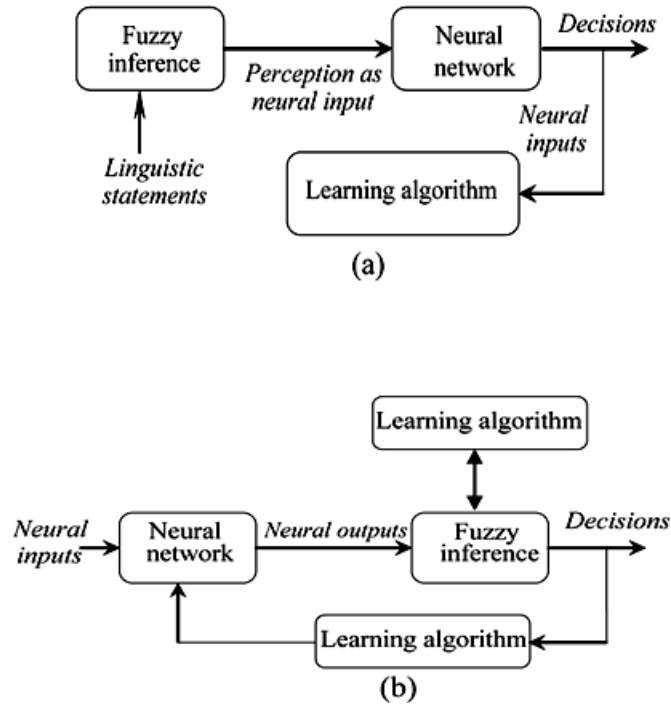
Two possible models of fuzzy neural systems are:

- In response to linguistic statements, the fuzzy interface block provides an input vector to a m layer neural network. The neural network can be adapted (trained) to yield the desired common outputs or decisions (Figure 5a).
- A multi-layered neural network drives the fuzzy inference mechanism (Figure 5b).

Wavelet and Neural Networks

Wavelet Neural Networks (WNNs) is an approach towards the learning function. Wavelet networks, combining the wavelet theory and neural networks, utilize wavelets as the basic function to construct a network. A wavelet function is a local function and influences the network's output only in some local range. The WNN shows surprising effectiveness in solving the conventional problems of poor convergence or even divergence encountered in other kinds of neural networks. The WNN consists usually of three layers. The detailed description of the calculation steps of WNN are explained in Telfer and Kadambe (1992).

Figure 5. a) The first model of fuzzy neural system, b) The second model of fuzzy neural system (adapted from Fuller, 2000)



METEOROLOGICAL-BASED SOAR RADIATION DATA ANALYSIS, MODELING AND FORECASTING

Knowledge of the local solar radiation is essential for the proper design of building energy systems, solar energy systems and a good evaluation of thermal environment within buildings (Davies and McKay, 1982; Hsieh, 1986; Iqbal, 1983; Kalogirou, 2009; Lu *et al.*, 1998; Sherry and Justus, 1984; Lewis, 1984). Solar radiation received at the flat surface is the most important as far as designing and operation of solar energy systems. All solar energy applications require readily available, site-oriented and long-term solar radiation data. A typical solar radiation database comprises of global, direct and diffuse solar irradiance, sunshine duration and complementary data like cloud cover, atmospheric turbidity, humidity, air temperature, wind speed, etc (Davies and McKay, 1982; Hsieh, 1986; Iqbal, 1983; Kalogirou, 2009; Swartman

and Ogunlande, 1967). The best database would be the long-term measured data at the site of the proposed solar energy system. However, most of these stations do not provide complete solar data information, mainly due to the high costs for operation and measuring instruments. For instance, global radiation is the most frequently measured parameter, while its two components (diffuse and direct irradiance) are often not measured. This limited spatial and temporal coverage of solar radiation measurements dictates the need for the development of the solar radiation models. Since the direct (beam) irradiance is important in designing solar energy systems, such as high-temperature heat engines and high-intensity solar cells, emphasis is often put on modeling the beam (direct radiation) component. There are two categories of solar radiation models, available that predict the beam component or sky component based on other more readily measured quantities: a) parametric models, and b) decomposition models.

On the other hand, most of the solar radiation applications involved tilted surfaces, requiring the knowledge of both diffuse and direct components of global radiation falling on a horizontal surface. There are also a number of problems that may arise during the measurement of the synoptic and solar radiation. The most common causes of the errors are related to the equipment and their respective sensitivities. Another major cause of errors is site operation conditions, such as instrument proximity to shading elements, electrical and magnetic field interferences, bird and insect activity and weather elements. There is, therefore a need to identify erroneous data and exclude and correct them. In this regard, quality control methodologies and procedures were developed over the years, based on physical and statistical tests to remove suspected outliers in the datasets. The available datasets were used to fine tune the proposed models.

When solar radiation data is unavailable, it is possible to get reasonable accurate estimates using the proposed models which rely on alternative synoptic information or on the measurement at other locations. These models are also useful to fill-in any gaps in the measured radiation datasets. Over the years, various empirical models have been developed for different geographical and meteorological conditions.

The insulation available to a solar energy system, such as a photovoltaic system with given orientation and inclination depends on the local climate and geographical location. To calculate inclined insolation, it is necessary to know beam and diffuse components of the global irradiance. However, as most weather stations provide only global irradiance data, a correlation developed between the global and diffuse component using measured values of these two quantities is used to calculate the diffuse component of global insolation. Correlated quantities can be divided into four groups: daily global insolation and its diffuse component; monthly mean daily global insolation and its diffuse component; monthly

mean hourly global insolation and its diffuse component; and hourly global insolation and its diffuse component (Davies and McKay, 1982). Solar radiation models may be categorized into two groups: parametric models and decomposition models; parametric models require detailed information of atmospheric conditions, whereas decomposition models generally employ global radiation to predict direct and diffuse components (Davies and McKay, 1982). Wong and Chow (2001) and Muneer *et al.* (2007) have presented detailed reviews of these two kinds of models, as well as in depth discussions of their characteristics and performances. Several correlation models correlating diffuse fraction (ratio of diffuse to global radiation) and clearness index (ratio of horizontal global radiation to extra-terrestrial radiation) have been developed under various climatic conditions (Wong and Chow, 2001). These correlations are mostly latitude dependent (Lu *et al.* 1998). Diffuse-global correlations have been developed that include atmospheric effect such as dry bulb temperature and relative humidity (Abdallah, 1994; Muneer, 2004; Muneer *et al.*, 2007).

CONVENTIONAL MODELS FOR SOLAR RADIATION

Most solar energy applications such as the simulation of solar energy systems require, at the least, knowledge of hourly values of solar radiation on a tilted and arbitrarily oriented surface. Knowledge of direct irradiance is important in applications where the solar radiation is concentrated, either to raise the temperature of the system, as in solar-thermal energy technologies, or to increase the electric current in solar cells, as in PV systems. In the absence of direct irradiance data, this component of solar radiation maybe estimated using decomposition models. They calculate direct irradiance from global solar irradiance on a horizontal surface. These models are based on the regressions between two dimensionless indices:

the clearness index, K_T (horizontal global irradiance/horizontal extra-terrestrial irradiance) and the direct solar transmittance, k_B (direct normal irradiance/extra-terrestrial irradiance).

As we already mentioned in a previous section of this chapter, there are two categories of solar radiation models, available in the literature, that predict the beam component of the based on other more readily measured quantities: a) parametric models, and b) decomposition models. Parametric models require detailed information of atmospheric conditions. Meteorological parameters used as predictors include the type, amount, and distribution of clouds or other observations, such as the fractional sunshine, atmospheric turbidity and precipitable water content (Angstrom, 1929; Cartwright, 1993; Iqbal, 1978 and 1980; Kasten and Czapla, 1980; Machler and Iqbal, 1985; Muneer and Saluja, 1985; Page, 1961; Rietveld, 1978; Trabea and Shaltout, 2000). One of the most used models by the engineers and architects is the ASHRAE algorithm (ASRE, 1999), while the Iqbal model (1980) offers extra accuracy over more conventional models as reviewed by Gueymard (1993a, b). Development of correlation models that predict the beam or sky radiation using other solar radiation measurements is also possible. Decomposition models usually use information only on global radiation to predict the beam and sky components. These relationships are usually expressed in terms of the irradiances which are the time integrals (usually over 1h) of the radiant flux or irradiance. Decomposition models developed to estimate direct and diffuse irradiance from global irradiance data were found in the literature (Akinoglu and Ecevit, 1990; Almorox and Hontoria, 1967; Bahlel *et al.* 1987; Balirci, 2009; Carroll, 1985; Collaress-Pereira and Rabl, 1979; Klucher, 1979; Liu and Jorda, 1960; Lewis, 1983; Roa *et al.* 1984; Trabea and Shaltout, 2000).

There are several relationships that relate the global radiation to other meteorological and climatologic parameters such as sunshine hours, air temperature, cloud coverage, and relative

humidity. The amount of solar energy per unit time, at the mean distance from the sun, received on the unit area perpendicular to the direction of propagation of the solar radiation outside the atmosphere is called the *solar constant*, SC . When the sun is closest to the earth, on January 3, the solar constant is about 1400 W/m^2 , while when the sun is farthest away, on July 4th, it is about 1330 W/m^2 , and the averages value adopted in 2000 by the American Society of Testing and Materials is 1366.1 W/m^2 .

Parametric Models

One of the first model developed to estimate direct normal irradiance I_0 (W/m^2) described by

Iqbal (1980) is given by:

$$I_0 = 0.9751 E_0 \cdot SC \cdot \tau_r \tau_o \tau_g \tau_w \tau_a \quad (6)$$

where the factor 0.9751 is included because the spectral interval considered is $0.3\text{-}3 \mu\text{m}$, E_0 (dimensionless) is the eccentricity correction-factor of the Earth's orbit and is given by:

$$E_0 = 1.00011 + 0.034221 \cos(\Gamma) + 0.00128 \sin(\Gamma) + 0.000719 \cos(2\Gamma) + 0.000077 \sin(2\Gamma) \quad (7)$$

The day angle Γ (radians) is given by:

$$\Gamma = 2\pi \left(\frac{N - 1}{365} \right) \quad (8)$$

where N is the day number of the year, ranging from 1 on 1st January to 365 on 31st December.

τ_r , τ_o , τ_g , τ_w , and τ_a (dimensionless) are the Rayleigh, ozone, gas, water, and aerosol scattering transmittances, respectively. The expressions for computing these transmittances can be found in (Iqbal, 1983) or elsewhere in the literature.

A simpler procedure for solar radiation is adopted in ASHARE (1999) and widely used in the engineering and architectural communities. The direct normal irradiance I_n (W/m^2) is given by:

$$I_n = (C_n) A \cdot \exp\left(\frac{B}{\sec(\Phi)}\right) \quad (9)$$

where A (W/m^2) is the apparent extraterrestrial irradiance, which takes in account the variations in the Sun-Earth distance (see Table 1 of Muneer (2004)) for their values), and Φ is the zenith angle (degrees). The variable B (dimensionless) represents an overall broadband value of the atmospheric attenuation coefficient for the basic atmosphere of Threlkeld and Jordan (1958). C_n (dimensionless) is the clearness number and the map of C_n for the USA is provided in the ASHARE handbook. C_n is the ratio of the direct normal irradiance calculated with the local mean clear-day water-vapor to the direct normal irradiance calculated with water vapor according to the basic atmosphere. Equation (8) was developed for sea level conditions. It can be adapted for other atmospheric pressures by:

$$I_n = (C_n) A \cdot \exp\left(\frac{B}{\sec(\Phi)} \cdot \frac{p}{p_0}\right) \quad (10)$$

where p (mbar) is the actual local air pressure and p_0 is the standard pressure (1013.25 mbar).

In the above equation, the term $(p/p_0)\sec(\Phi)$ approximates to the air mass, with the assumptions that the curvature of the Earth and the refraction of air are negligible.

An all-sky broadband empirical algorithm, the so-called Meteorological Radiation Model (MRM), developed by Muneer *et al.* (2007) that utilize dry and wet-bulb temperature or relative humidity along with sunshine duration. The model can estimate horizontal solar components (direct, diffuse, and global irradiation on an hourly, daily,

or monthly basis and is an adaptation of the Iqbal model, discussed in the above paragraph. Monthly average hourly and daily irradiance are obtained via summing the long-term computed and measured values. The correlation in this model is given by:

$$DBR = \frac{I_D}{I_B} = 0.285211k_B^{-1.00648} \quad (11)$$

and

$$I_B = (SF) \cdot SC \cdot \tau_r \tau_o \tau_g \tau_w \tau_a \quad (12)$$

finally

$$I_G = I_B + I_D \quad (13)$$

where I_D is diffuse, I_B is beam/direct, and I_G is global irradiation (W/m^2), k_B is beam clearness index (dimensionless), and SF is sunshine fraction (dimensionless). Interested reader can find the full description of the model and the relationships for the transmittances in (Iqbal, 1983; Kalogirou, 2009).

Kasten and Czeplak (1980) developed an algorithm (so-called Cloud-Cover Radiation Model or CRN) capable of generating hour-by-hour global, diffuse, and direct horizontal irradiance, by using only cloud-cover data. In order to determine global radiation I_G from total cloud amount N in oktas, the radiation under cloudless sky, I_{Gc} is required. I_{Gc} depends on solar elevation angle α , and may be obtained via the linear parametrization as given by Kasten and Czeplak (1980):

$$I_{Gc} = (A \cdot \sin \sin(\alpha) - B) \quad (14)$$

The ratio of global radiation I_G for a given cloud amount N (okta), to I_{Gc} has been shown to be independent of the solar elevation α :

$$\frac{I_G}{I_{Gc}} = 1 - C \left(\frac{N}{8} \right)^D \quad (15)$$

The diffuse component is then calculated by using estimated global irradiation from Equation (12):

$$\frac{I_D}{I_G} = 0.3 + 0.7 \left(\frac{N}{8} \right)^2 \quad (16)$$

The direct component will then be calculated as the difference of global and diffuse irradiation. The coefficients A , B , C , and D involved in this model are fitted against the experimental data. Muneer *et al.* (2007) fitted these coefficients for UK locations.

Estimation of the Hourly Diffuse Radiation on a Horizontal Surface Using Decomposition Models

Values of global and diffuse radiations for individual hours are essential for research and engineering applications. Hourly global radiations on horizontal surfaces are available for many stations, but relatively few stations measure the hourly diffuse radiation. Decomposition models have, therefore, been developed to predict the diffuse radiation using the measured global data.

The models are based on the correlations between the clearness index K_T (dimensionless) and the diffuse fraction k_d (dimensionless), diffuse coefficient k_D (dimensionless) or the direct transmittance k_B (dimensionless) where:

$$K_T = \frac{I_G}{I_0}, k_d = \frac{I_d}{I_G}, k_D = \frac{I_D}{I_0}, k_B = \frac{I_B}{I_0}, \quad (17)$$

I_G , I_B , I_D and I_0 being the global, direct, diffuse and extraterrestrial irradiances respectively, on a horizontal surface (all in MJ/m^2).

The relationships permitting the determination, for a horizontal surface, of the instantaneous intensity of diffuse radiation on clear days, the long-term average hourly and daily sums of diffuse radiation, and the daily sums of diffuse radiation for various categories of days of differing degrees of cloudiness, with data from 98 localities in the USA and Canada, were studied by Liu and Jordan (1960). The transmission coefficient for total radiation on a horizontal surface is given by the intensity of total radiation (i.e. direct I_B plus diffuse I_D) incident upon a horizontal surface I_G divided by the intensity of solar radiation incident upon a horizontal surface outside the atmosphere of the Earth I_0 . The correlation between the intensities of direct and total radiations on clear days is given by:

$$k_D = 0.271 - 0.2939k_B \quad (18)$$

since

$$K_T = \frac{I_B + I_D}{I_0} = k_B + k_D \quad (19)$$

then

$$k_D = 0.384 - 0.416K_T \quad (20)$$

Following the work of Liu and Jordan (1960) several researchers were involved in the development of solar radiation models. Orgill and Hollands (1977) using the clearness index only developed a model to estimate diffuse radiation fraction, based on the measurements of global and radiation at Toronto, Canada. Erbs *et al.* (1982) studied the same kind of correlations with data from 5 stations, located in the Southern USA. The data were of short duration, ranging from 1 to 4 years. In each station, hourly values of normal direct irradiance and global irradiance on a horizontal surface were registered. Diffuse irradiance was obtained as the difference of these

quantities. Spencer (1982) studied the latitude dependence on the mean daily diffuse radiation with data from 5 stations in Australia. Reindl *et al.* (1990) estimated the diffuse fraction k_d using two different models developed with measurements of global and diffuse irradiance on a horizontal surface registered at 5 locations in the USA and Europe. Lam and Li (1993) studied the correlation between global solar radiation and its direct and diffuse components for Hong Kong with the measured data in 1991–1994. A hybrid correlation model based on hourly measured data for the prediction of hourly direct and diffuse components from the global radiation for Hong Kong was developed in their study.

Skartveit and Olseth (1987) showed that the diffuse fraction depends also on other parameters such as solar elevation, temperature and relative humidity. Similar arguments were found in the literature (Cartwright, 1993; Kasetn and Czelpak, 1980; Muneer and Saluja, 1985; Lui *et al.* 1998; Machler and Iqbal, 1985). They estimated the direct irradiance I_B from the global irradiance G_t and from the solar elevation angle, Φ for Bergen, Norway, with the following equation:

$$I_B = \frac{G_t(1 - \psi)}{\sin(\Phi)} \quad (21)$$

where ψ is a function of K_T and the solar elevation angle, Φ (degrees). The model was validated with data collected in Aas, Norway, Vancouver, Canada and 10 other stations worldwide. Details of this model can also be found in (Gueymard, 1993b; Lam and Li, 1993).

A quasi-physical model for converting hourly global horizontal to direct normal insolation proposed by Maxwell (1987) was reviewed by Batlles *et al.* (2000). The model combines a clear physical model with experimental fits for other conditions. The direct irradiance I_B is given by:

$$I_B = I_0 \left[\psi - (d_4 - d_5 \exp(m_a d_6)) \right] \quad (22)$$

where I_0 is the extraterrestrial irradiance, is a function of the air mass m_a (dimensionless) and is given by:

$$\psi = 0.866 - 0.122m_a + 0.121m_a^2 - 0.00065m_a^3 + 0.000014m_a^4 \quad (23)$$

and d_4 , d_5 and d_6 are functions of the clearness index K_T , determined from the experimental data. Louche *et al.* (1991) used the clearness index K_T to estimate the transmittance of beam radiation k_B . The correlation was tested by using data collected at Ajaccio, Corsica, France between 1981 and 1983. Vignola and McDaniels (1986) studied the daily, 10-day and monthly average beam-global correlations for 7 sites in Oregon and Idaho, USA. The beam-global correlations vary with time of year in a manner similar to the seasonal variations exhibited by diffuse-global correlations.

Correlations of Average Daily Solar Radiation with Hour of Sunshine and Other Meteorological Parameters

The first correlation proposed for estimating the monthly average daily global radiation is based on the method of Angström (1929). The original Angström-type regression equation related the monthly average daily radiation to clear day radiation in a given location and average fraction of possible sunshine hours:

$$\frac{H}{H_c} = a + b \left(\frac{S}{S_0} \right) \quad (24)$$

A basic difficulty with Equation (7) lies in the ambiguity of the terms S/S_c and H_c . Page (1961) and other researchers (Abdallah, 1994; Bakirci,

2009; Batlles et al. 2000; Camps and Soler, 1995; Garrison, 1985; Reidl *et al.* 1990) have modified the method to base it on a horizontal surface rather than on clear radiation (Gueymard 1993a):

$$\frac{H}{H_0} = a + b \left(\frac{S}{S_0} \right) \quad (25)$$

where H is the monthly average daily global radiation, H_0 the monthly average daily extraterrestrial radiation, S the monthly average daily hours of bright sunshine, S_0 the monthly average day length, and a and b are the empirical constants, determined from the experimental data. The monthly average daily extraterrestrial radiation on a horizontal surface (H_0) can be computed from the following relationship:

$$H_0 = \frac{24}{\pi} SC \left(1 + 0.033 \frac{360N}{365} \right) \left[\cos \cos(L) \cos \cos(\delta) \cos(\omega_s) + \left(\frac{2\pi\omega_s}{360} \right) \sin \left(\frac{2\pi\omega_s}{360} \right) \sin(L) \sin(\delta) \right] \quad (26)$$

where L is the local latitude, δ is the declination, Φ is the zenith angle, and ω_s is the mean sunrise hour angle. The solar declination and the mean sunrise hour angle are given by the following equations (Gueymard 1993a; Orgill and Hollands, 1977):

$$\delta = 23.45 \sin \left[\frac{360(N + 284)}{365} \right] \quad (27)$$

and

$$\omega_s = \arccos(-\tan(\delta) \tan(L)) \quad (28)$$

here N is the N th day of the year, counted from January 1st of each year. The sunset hour angle is also used to compute the maximum possible sunshine hours S_0 , for a given month, from the following equation:

$$S_0 = \left(\frac{2}{15} \right) \omega_s \quad (29)$$

Lewis (1983) estimates monthly average daily global radiation on a horizontal surface by the following equation:

$$H = a(RH)^b \quad (30)$$

where RH is the relative humidity, a and b empirical parameters.

Swartman and Ogulande (1967) proposed the following models (31) and (32) for the global solar radiation (GSR) prediction:

$$H = a + b \left(\frac{S}{S_0} \right) + cRH \quad (31)$$

and

$$H = a \left(\frac{S}{S_0} \right)^b + RH^c \quad (32)$$

In the Equations (31) and (32) parameters a , b , and c are empirical coefficients. The following relationship (33) between the solar radiation and sunshine hours was proposed by Almorox and Hontoria (1967):

$$H = a + b \cdot \exp \left(\frac{S}{S_0} \right) \quad (33)$$

where a and b are empirical coefficients.

Bahlel *et al.* (1987) developed a 4-parameter model for estimating the GSR:

$$\frac{H}{H_0} = a + b \left(\frac{S}{S_0} \right) + c \left(\frac{S}{S_0} \right)^2 + d \left(\frac{S}{S_0} \right)^3 \quad (34)$$

Again, parameters a , b , c and d are empirical coefficients, fitted to the measured data.

Following equation has been proposed by Akinoglu and Ecevit (1990) for estimating the GSR:

$$\frac{H}{H_0} = a + b \left(\frac{S}{S_0} \right) + c \left(\frac{S}{S_0} \right)^2 \quad (35)$$

here a , b , and c are empirical coefficients, as in the previous relationships.

Abdullah (1994) suggested the flowing model (36) which includes the mainly daily temperature in the global solar radiation estimate:

$$\frac{H}{H_0} = a + b \left(\frac{S}{S_0} \right) + cRH + dT \quad (36)$$

where T is the daily mean air temperature and a - d are empirical coefficients.

Trabea and Shaltout (2000) related the daily global radiation to sunshine duration, relative humidity, maximum air temperature, mean daily vapor pressure and mean daily sea level pressure to calculate H (37) at five stations in Egypt as follows:

$$\frac{H}{H_0} = a + b \left(\frac{S}{S_0} \right) + cT_{\max}dV + eRH + fP \quad (37)$$

where a , b , c , d , e , and f are regression coefficients, $T_{\max}$ is the maximum air temperature, RH is the relative humidity (%) and P is the ration between mean sea level pressure and mean daily vapor pressure (the ration of MSL to V). Recently, Bakirci (2009) developed the following model (Camps and Soler, 1995) for estimating the solar radiation (38), using long-term measurements at several locations in Turkey:

$$H = a + b \left(\frac{S}{S_0} \right) + c \exp \left(\frac{S}{S_0} \right) \quad (38)$$

where a , b and c are empirical parameters.

On the other hand, the extraterrestrial solar radiation, G_{on} measured on the plane normal to the radiation on the N th day of the year, varies between the maximum and the minimum values of the solar constant (SC) and can be calculated by (Almorox and Hontoria, 1967; Davies and McKay, 1982; Klucher, 1979), using the Equation (39):

$$G_{on} = SC \cdot \left[1 + 0.033 \left(\frac{360N}{365} \right) \right] \quad (39)$$

On a surface parallel to the ground, the rate of solar radiation, G_{0N} , incident on this extraterrestrial horizontal surface at a given time of the year is given by:

$$\begin{aligned} G_{0N} &= G_{on} \cos(\Phi) \\ &= SC \cdot \left[1 + 0.033 \left(\frac{360N}{365} \right) \right] \\ &\quad [\cos \cos(L) \cos \cos(\delta) \cos(h) \\ &\quad + \sin \sin(L) \sin(\delta)] \end{aligned} \quad (40)$$

here h is the hour angle.

The total radiation, H_0 , incident on an extra-terrestrial horizontal surface during a day can be obtained by the integration of the Equation (40) over a period from sunrise to sunset. To compute the extraterrestrial radiation the Equation (40) is integrated between hour angles, h_1 and h_2 , so:

$$\begin{aligned} I_0 &= \frac{12 \times 3600 S}{\pi} \left[1 + 0.033 \left(\frac{360N}{365} \right) \right] \\ &\quad \times \{ \cos \cos(L) \cos \cos(\delta) \cos(h_2 - h_1) \\ &\quad + \left[\frac{\pi(h_2 - h_1)}{180} \right] \sin \sin(L) \sin(\delta) \} \end{aligned} \quad (41)$$

It should be noted the limits h_1 and h_2 may define any time period other than 1 h. A comprehensive list of definitions and terminology that include those related to the solar radiation can be found in (Davies and McKay, 1982; Iqbal, 1983) or elsewhere in the literature. For example, the *ir-radiance* (W/m^2) is the rate of radiant energy falling

on a surface per unit of area of the surface, while the *irradiation* (J/m^2) is incident energy per unit of area of a surface, obtained by integrating the irradiance over a specific time interval. Specifically, for solar irradiance this is called *insolation*.

The solar radiation reaching the earth's surface is much lower than G_{on} because a large part of it is scattered, reflected back out into the space, and absorbed by the atmosphere. Some of the scattered radiation, the so-called *diffuse radiation* reaches the earth's surface from the entire sky vault. The solar heat coming directly through the atmosphere is called *direct* or *beam radiation*. The insulation received by a surface on a earth is the sum of diffuse radiation and the normal component of beam radiation. The solar heat at any pint on earth depends on the ozone layer thickness, the distance travelled through the atmosphere, the amount of haze in the air, and the extent of the cloud cover. The degree of attenuation of solar radiation traveling through the earth's radiation depends on the length of the path and the characteristics of the medium traversed. In solar radiation calculations, one standard air mass is defined as the path's length traversed in reaching the sea level when the sun is a zenith (the vertical point of the observation).

TERRESTRIAL RADIATION

To determine the long-term performances of a solar system, the knowledge of the long-term monthly average daily insulation data for that site are required. Daily mean total solar radiation (direct plus diffuse) incident on a horizontal surface is available from various sources (radiation maps, metrological service database). In these sources, data, such as 24 h average temperature, monthly average daily radiation on a horizontal surface, $\bar{H}$ ($MJ/m^2 \cdot d$), and monthly average clearness index, $\bar{K}_T$ are given together with other parameters. The monthly average clearness index (42) is defined as:

$$\bar{K}_T = \frac{\bar{H}}{\bar{H}_0} \quad (42)$$

where, $\bar{H}_0$ is the monthly average daily total insolation on an extraterrestrial horizontal surface (MJ/m^2). The bar signifies a long-term average. The values of $\bar{H}_0$ for each month function of latitude can be found in Table 2.5 of Davies and McKay, (1982).

To design or to predict the performance of a solar energy system requires hourly values of radiation. These types of data can be obtained, using different correlations from the long-term average daily radiation data, such as the Liu and Jordan (1977) correlation or the Collarees-Pereira (1979) correlation. The ration hourly total radiation to daily radiation, using the Collarees-Pereira correlation is given by (43):

$$r = \frac{\pi}{24} [\alpha + \beta \cos(h)] \frac{\cos(h) - \cos(h_{ss})}{\sin(h_{ss}) - \left(\frac{2\pi h_{ss}}{360}\right) \cos(h_{ss})} \quad (43)$$

here, h_{ss} is the sunset hour angle (degrees), h is the hour angle at the midpoint of each hour, and the parameters α and β are given by (44) and (45):

$$\alpha = 0.409 + 0.5016 \cdot \sin(h_{ss} - 60) \quad (44)$$

$$\beta = 0.6609 - 0.4767 \cdot \sin(h_{ss} - 60) \quad (45)$$

The solar collectors or PV panels are usually installed at an angle to increase the amount of radiation intercepted and to reduce reflection and cosine losses. System designers need solar radiation data on such tilted surfaces; measured or estimated. Most of the time solar radiation is available either for normal incidence or for horizontal surfaces. The amount of insulation on a surface at a given location for a given time depends on the orientation and slope of the surface.

A flat surface absorbs beam (I_{Bt}), diffuse (I_{Dt}), and ground-reflected (I_{Gt}) solar radiation, so the total radiation is given by (46):

$$I_t = I_{Bt} + I_{Dt} + I_{Gt} \quad (46)$$

The beam radiation on a tilted surface (see Figure 6) is given by the following relationship:

$$I_{Bt} = I_{Bn} \cdot \cos(\theta) \quad (47)$$

While on a horizontal surface, it is given by:

$$I_B = I_{Bn} \cdot \cos(\Phi) \quad (48)$$

The beam radiation tilt factor is defined by the (48) equation, as:

$$R_B = \frac{I_{Bt}}{I_B} = \frac{\cos(\theta)}{\cos(\Phi)} \quad (49)$$

There are several models to compute the solar radiation on a tilted surface. The diffuse radiation on a tilted surface, according to the isotropic radiation model [51, 52] can be computed using:

$$I_{Dt} = I_D \left[\frac{1 + \cos(\beta)}{2} \right] \quad (50)$$

Here I_D is the diffuse radiation ($I_D = 2I_R$), and I_R is the diffuse sky radiation ($W/m^2 \cdot rad$). The ground-reflected radiation on a tilted surface is expressed as:

$$I_{Gt} = \rho_G \cdot (I_B + I_D) \left[\frac{1 - \cos(\beta)}{2} \right] \quad (51)$$

Combining (12), (13), (14) and (15), we get:

$$I_t = R_B I_B + I_D \left[\frac{1 + \cos(\beta)}{2} \right] + \rho_G (I_B + I_D) \left[\frac{1 - \cos(\beta)}{2} \right] \quad (52)$$

The total radiation on a horizontal surface, I , is the sum of horizontal beam and diffuse radiation, as shown in Equation (53):

$$I = I_B + I_D \quad (53)$$

The isotropic sky model is the simplest model, assuming that all diffuse radiation is uniformly distributed over the sky and that the reflection on the ground is diffuse. The model developed by Kloucher (1979), takes into account the horizon brightening, and the effect of circumsolar radiation, and the total irradiance on a tilted plane (Hsieh, 1986) is given by:

$$I_t = I_B R_B + I_D \cdot \left[\frac{1 + \cos(\beta)}{2} \right] [1 + K_t \sin^3(\frac{\beta}{2})] \\ [1 + K_t \cos^2(\beta) \sin^3(\Phi)] + (I_B + I_D) \cdot \rho_G \cdot \left[\frac{1 - \cos(\beta)}{2} \right] \quad (54)$$

where K_t is a clearness index given by:

Figure 6. Beam radiation on horizontal and tilted surfaces



$$K_T = 1 - \left[\frac{I_D}{I_B + I_D} \right]^2$$

Under overcast skies, the clearness index is 0 and the model reduces to the isotropic model. In the Hay-Davies (1980), the diffuse radiation is composed of an isotropic and circumsolar component, while the horizon brightening is not taken into account. Reflection from the ground is computed as in the isotropic mode. The total irradiance (55) is computed by:

$$I_t = (I_B + I_D) \cdot R_B + I_D (1 - A) \cdot \left[\frac{1 + \cos \cos(\beta)}{2} \right] + (I_B + I_D) \rho_G \left[\frac{1 - \cos(\beta)}{2} \right] \quad (55)$$

where represents the transmittance through atmosphere for beam radiation.

The Reindl model (1990) takes also into account the horizon brightening, and the total irradiance on a tilted surface can be calculated by:

$$I_t = (I_B + I_D) R_B + I_D (1 - A) \left[\frac{1 + \cos \cos(\beta)}{2} \right] \left[1 + \sqrt{\frac{I_B}{I_B + I_D}} \sin^3 \left(\frac{\beta}{2} \right) \right] + (I_B + I_D) \rho \left[\frac{1 - \cos(\beta)}{2} \right] \quad (56)$$

Reflection on the ground is again as in the isotropic model. Due to the inclusion of the horizon brightening, Reindl (1990) model gives slightly higher diffuse irradiance than the previous one.

INSULATION ON TILTED SURFACES

The amount of insulation on a terrestrial surface at a given location and time depends on the ori-

entation and slope of the surface. Most of measured radiation data are for either normal incidence or horizontal, which need to be converted to radiation on tilted surfaces. There are several empirical relationships developed over the years for such estimates. In the Liu and Jordan (1977) method the diffuse and total radiation ratio for a horizontal surface is expressed in terms of monthly clearness index, $\bar{K}_T$ as:

$$\frac{\bar{H}_D}{\bar{H}} = 1.390 - 4.027 \bar{K}_T - 3.108 \bar{K}_T^3 \quad (57)$$

Collares-Pereira and Rabl (1979) extended previous model by considering the sunset hour angle:

$$\frac{\bar{H}_D}{\bar{H}} = 0.775 + 0.0065 (h_{ss} - 90) - [0.505 + 0.00455 (h_{ss} - 90)] \cos \pi (115 \bar{K}_T - 103) \quad (58)$$

Interested readers can learn more about the solar radiation models and estimate procedures in the following review papers (Muneer, 2004; Muneer *et al.* 2007) or elsewhere in the literature.

APPLICATION OF AI TECHNIQUES FOR SOLAR RADIATION PREDICTION AND MODELING

Meteorological data such as solar radiation, ambient temperature, relative humidity, wind speed, clearness index and sunshine duration are accepted as dependable and widely variable in renewable energy sources. It is therefore required to be able to formulate forecasting and estimation models of these meteorological data. These data play a very important role in solar energy systems. However, in many cases these data are not available owing to the high cost and complexity of the instrumentation needed to record them. Solar energy is a

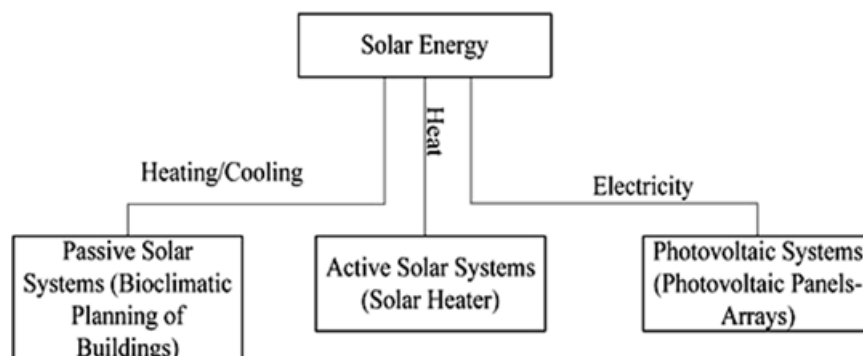
sustainable, safe and abundant energy resource and therefore there are no restrictions of time and space for its exploitation. Concerning the exploitation of solar energy, it is divided into three basic applications: passive solar systems, active solar systems and photovoltaic systems (Figure 7). Passive and active solar systems exploit the thermal energy of global solar irradiance, while PV systems convert global solar irradiance to electricity. Estimating global solar irradiance on tilted surfaces is necessary as the majority of solar energy systems are inclined according to the site of installation and utilization. Moreover, beam and diffuse components of global solar irradiance on inclined surfaces are essential in order to calculate the electric power of photovoltaic systems, design solar thermal systems and to evaluate their long-term average performance.

Despite the fact that many meteorological stations measure global and diffuse irradiation received on horizontal surfaces, the data on inclined surfaces are not available and are estimated with several models, using the components of global solar irradiance on horizontal surfaces. It must be noted that the knowledge of the components of global solar irradiance on horizontal surfaces is essential for the prediction of global solar irradiance on tilted surfaces, as it is difficult to develop a simple model converting solar irradiance received by the horizontal plane to that arriving at an inclined area for two main reasons

(Wong and Chow, 2001): 1) Global solar irradiance reaching at tilted surface includes irradiance reflected from the surroundings; and 2) The view angle of a tilted surface cuts out a limited solid angle of the sky. This sky irradiation not only depends on the tilt angle, on the azimuth of the collector and on the solar elevation and azimuth but also on the cloud conditions. The models for predicting global solar irradiance on tilted surfaces are classified as isotropic and anisotropic. The isotropic models (Bugler, 1977; Badescu, 2002; Koronakis, 1986; Liu and Jordan, 1960; 1962, Ma and Iqbal, 1983; Tian *et al.* 2002) predict the diffuse irradiance on a tilted surface, assuming the uniformity of diffuse sky irradiance over the sky dome. However, this theory is not correct (Kalogirou, 2009) and therefore additional models, the so-called anisotropic models were developed. In the anisotropic models consider the sum of the anisotropy of the diffuse sky irradiance in the circumsolar region (sky near the solar disk) and the anisotropic diffuse component for the rest of the sky dome.

Solar radiation data are accepted as dependable and widely available renewable energy sources. It is, therefore, necessary to formulate forecasting and estimation models of these meteorological data. These data play a very important role in PV-systems sizing and design. The next sections of this chapter deal with overviews of the applications of various AI techniques in solar radiation estimation,

Figure 7. Basic applications of global solar irradiance (adapted from Behrang et al., 2010)



modeling and prediction. This includes modeling of the monthly, daily and hourly solar radiation, daily clearness index modeling, and insolation forecasting and prediction. As we pointed out in previous sections of this chapter, measurement data may suffer of several drawbacks, such poor quality data, not enough measurements, data gaps, while the traditional modeling and forecasting algorithms may be too complex and requiring large computer resources. An alternative way to avoid the above problems is to employ the AI techniques and emphasis is given to their growing use for data analysis and prediction, offering an effective alternative to more traditional statistical techniques.

ANN MODELS FOR SOLAR RADIATION ESTIMATION, PREDICTION, AND FORECASTING

Vergara-Dominguez *et al.* (1985) made one of the first attempts, back in 1985 of the using an automatic process to generate and estimate daily global solar radiation. However, one of the first applications of a neural network for predicting daily solar radiation was made by Elizondo *et al.* in 1994. Their neural network model predicts solar radiation as a function of readily available weather data and other environmental variables. Four sites in the southeastern USA, i.e. Tifton, GA, Clayton, NC, Gainesville, FL, and Quincy, FL, were selected because of the existence of long-term daily weather data sets which included solar radiation. A combined total of 23 complete years of weather data sets were used in this model. The data sets were separated into 11 years for the training data set and 12 years for the testing data set. Daily observed values of minimum and maximum air temperature and precipitation, together with daily calculated values for day-length and clear sky radiation, were used as inputs for the neural network model. Day-length and clear sky radiation were calculated as a function of latitude,

day of year, solar angle, and solar constant. An optimum momentum, learning rate, and number of hidden nodes were determined for further use in the development of the neural network model. The neural network model was tested against the independent data set. Root mean square error varied from 2.92 to 3.64 MJ/m² and the coefficient of determination varied from 0.52 to 0.74 for the individual years used to test the accuracy of the model. Although this neural network model was developed and tested for a limited number of sites, the results suggest that it can be used to estimate daily solar radiation when measurements of only daily maximum and minimum air temperature and precipitation are available.

Williams and Zazueta (1994, 1996) proposed the use of feed-forward neural networks to estimate the daily solar radiation. The authors used as inputs other meteorological parameters such as precipitation, temperature, clear sky radiation, day length and day of the year. Mohandes *et al.* (1996) used data from 41 collection stations in Saudi Arabia. From these, the data for 31 stations were used to train a neural network and the data for the other 10 for testing the network. The input values to the network are latitude, longitude, altitude and sunshine duration. The results for the testing stations obtained are within 16.4% and indicate the viability of their approach for spatial modeling of solar radiation. Alawi and Hinai (1998) have used ANNs to predict solar radiation in areas not covered by direct measurement instrumentation. In this work, a novel approach using an artificial neural network was used to develop a model for analyzing the relationship between the Global Radiation (GR) and climatological variables, and to predict GR for locations not covered by the model's training data. The predicted global radiation values for the different locations (for different months) were then compared with the actual values. The input data to the network are the location, month, mean pressure, mean temperature, mean vapor pressure, mean relative humidity, mean wind speed and mean duration of

sunshine. The ANN model predicts solar radiation with an accuracy of 93% and mean absolute error of 7.3%. In addition, the model was also tested to predict GR values for the Seeb location over a 12 months period. The monthly predicted values of the ANN model compared to the actual GR values for Seeb produced an accuracy of 95% and a mean absolute percentage error of 5.43. Data for these locations were not included as part of the ANN training data. The results demonstrate the generalization capability of this novel approach over unseen data and its ability to produce accurate estimates. A RBF network has been used for prediction of daily solar radiation data in Algeria by Guessoum *et al.*, (1998).

A neural network approach for generating solar radiation artificial series has been proposed by Zufiria *et al.* (1999) to predict solar radiation for Spain. Togrul and Onat (1999) developed a model for the estimation of the solar radiation based on geographical and meteorological data in Elazige, Turkey. In this study, the effect of geographical and meteorological parameters on the monthly mean global solar radiation was investigated. A multiple linear regression was applied to six geographical and meteorological data sets, which were monthly, mean extraterrestrial radiation, the ratio of 'bright sunshine hours to the day-length, ambient and soil temperatures, humidity and sine of declination angle. The global solar radiation estimated from the models was compared with the 2-year measurement data set. It has been determined that these equations which express the 99th percentile of the incident solar radiation, have a -9% deviation from our measured values. Taken in account that the mean error of the forecast insolation by the single-stage neural network is about 30%, Kemmoku *et al.* (1999) proposed a multistage ANN to predict the insolation of the next day. The input data to the network are the average atmospheric pressure, predicted by another ANN and various weather data of the previous day. A first-stage neural network forecasts the average atmospheric pressure of the next day from atmospheric pressure

data of the previous day. A second-stage neural network forecasts the insolation level of the next day from the average atmospheric pressure and weather data of the previous day. A third-stage neural network forecasts the insolation of the next day from the insolation level and weather data of the previous day. The results obtained show a prediction accuracy of 20%. The authors propose a multi-stage NN method for forecasting the insolation of the next day. Figure 8 shows the block diagram of the multi-stage NN used for forecasting the insolation, proposed by Kemoku *et al.* (1999). Meteorological data at Omaezaki, Japan in 1988–1993 are used as input data, and the insulations in 1994 are forecast. The insulations forecast by the multi-stage and the single-stage neural networks are compared with the measured ones. The results show that the mean error reduces from about 30% (by the single-stage) to about 20% (by the multi-stage).

Hontoria *et al.* (1999 and 2001a) improved the generation of hourly solar radiation artificial series using MLP neural networks. While, Hontoria *et al.* (2001b, 2002) applied an upgraded recurrent MLP ANN, developed earlier for modeling the solar radiation. This model consists of the generation of synthetic series of hourly solar irradiation. The model presented is based on the capacity of the MLP for finding relations between variables for which interrelation is unknown explicitly. The information available can be included progressively at the series generator at different stages. Comparative study with other solar irradiation synthetic generation methods demonstrated the validity of the proposed model.

Mohandes *et al.* (1998) used RBF networks (Figure 9) for modeling monthly mean daily values of global solar radiation on horizontal surfaces and compared its performance with that of a MLP model and a classical regression model. The proposed network employs as inputs the latitude, longitude, altitude and sunshine duration for the prediction of solar radiation values. Mohandes *et al.* (2003) used solar radiation data from 41 sta-

Figure 8. Flowchart for insolation forecast using a multi-stage neural network (Adapted from Kemoku et al., 1999)

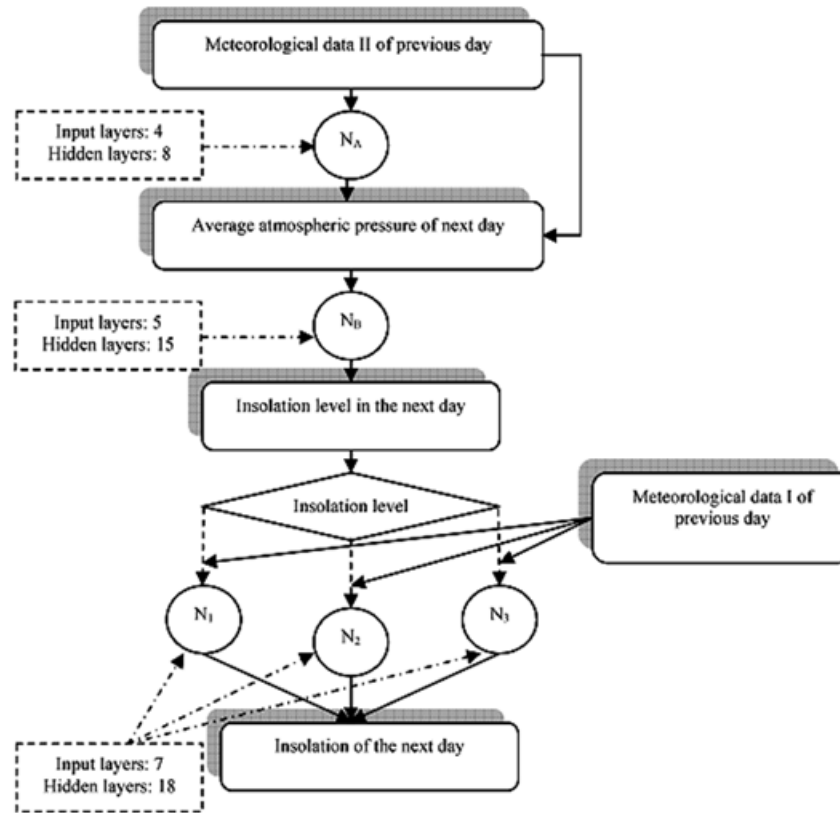
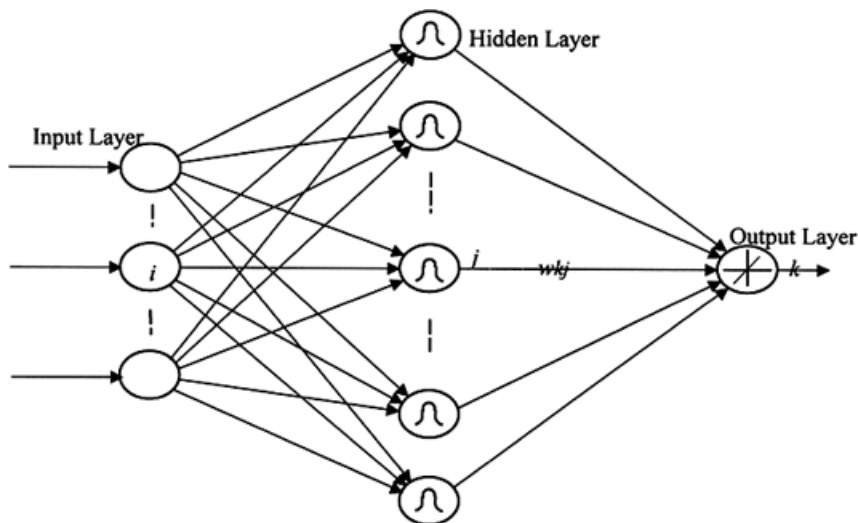


Figure 9. A radial basis functions neural network (Adapted from Mohandes et al., 2003)



tions that are spread over the Kingdom of Saudi Arabia, by using radial basis functions ANN. The solar radiation data from 31 locations are used for training the neural networks and the data from the remaining 10 locations are used for testing the estimated values. The testing data were not used in the modeling or training of the networks to give an indication of the performance of the system at unknown locations. Results indicate the viability of the radial basis for this kind of problem. The authors believed that by adding new data would further improve the models' performances. This is because the ANNs methods depend on learning from examples. The method should be applicable to any region, provided that samples of the solar radiation data from locations of all types of weather conditions are included in the training process. That is these methods are not limited to use in areas with solar conditions similar to Saudi Arabia, only.

Mihalakakou *et al.* (2000) developed a total solar radiation time series simulation model based on ANN and applied in Athens. The model with the least error was identified as a Neural Logic Network that incorporated Logic Rules that produced an RMS error 4.9% lower than that of the persistent approach. Sfetsos and Coonick (2000) introduced a simple approach for the forecasting of hourly solar radiation using various AI based techniques (ANNs, ANFIS). They also investigated other meteorological variables such as temperature, wind speed, pressure. A comprehensive discussion and review of the ANN applications in the renewable energy systems applications was published by Kalogirou (2001). Interested readers are strongly encouraged to read this paper for in depth presentation of the ANN applications in the renewable energy systems. In this paper the author presented various applications of the neural networks in renewable energy problems in a thematic rather than a chronological or any other order. This includes the use of ANNs in solar radiation and wind speed prediction, photovol-

taic systems, building services systems and load forecasting and prediction.

A Radial Basis Functions (RBF) and Multi-Layer Perception (MLP) methods to estimate solar radiation, by using long-term data from eight stations in Oman was developed and implemented by Drovlo *et al.* (2002). It is shown by these authors that both the RBF and MLP models performed well based on the root-mean-square error between the observed and estimated solar radiations. However, the RBF models are preferred since they require less computing power and are more accurate. The range of errors for the RBF networks was 0.83 to 10.08 MJ/m²/day, while the range of errors for MLP networks was 1.01 to 9.41 MJ/m²/day. As the authors mentioned in this paper the model can be used to estimate the solar radiation at any location in Oman, with a proper training. Kalogirou *et al.* (2002) used an ANN model for prediction of maximum solar radiation. The prediction of solar radiation is very important for many solar applications. Due to the very nature of solar radiation, many parameters can influence both its intensity and its availability and therefore it is difficult to employ analytical methods for such predictions. The input data that are used in their approach are those which influence mostly the availability and intensity of solar radiation, namely, the month, day of month, Julian day, season, mean ambient temperature and mean relative humidity (RH). A multilayer recurrent architecture (considered suitable for time series predictions) employing the standard back-propagation learning algorithm has been applied, here. Using the hourly records for one complete year, the maximum value of radiation and the mean daily values of temperature and relative humidity (RH) were calculated. The respective data for 11 months were used for the training and testing of the network, whereas the data for the remaining one month were used for the validation of the network. The training of the network was performed with adequate accuracy, with a correlation coefficient between the actual and the ANN predicted data of 0.9867. Also, the

sensitivity of the predictions to $\pm 20\%$ variation in temperature and RH give correlation coefficients of 0.9858 to 0.9875, which are considered satisfactory. This is considered as an adequate accuracy for such predictions.

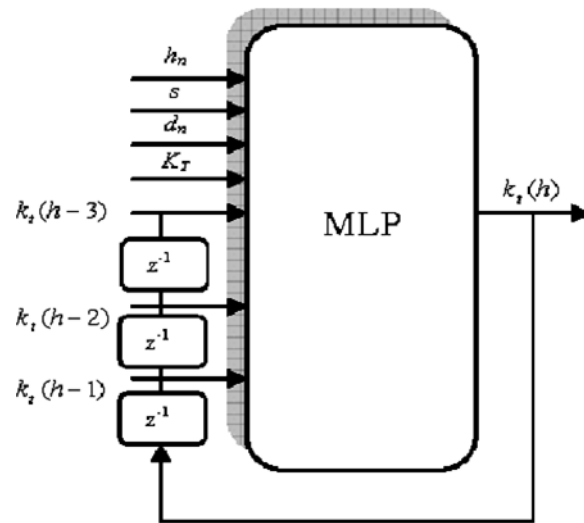
ANN based models for estimation of monthly mean daily and hourly values of solar global radiation were proposed by Reddy and Manish (2003). Solar radiation data from 11 stations spread over India, round the year, have been used for training and testing the ANN. The results of the ANN model have been compared with other empirical regression models. The solar radiation estimations by ANN were in good agreement with the actual values and were superior to those of other available models. The maximum mean absolute relative deviation of predicted hourly global radiation tested is 4.07%. Their results indicate that the ANN models are a promising candidate for evaluating the solar global radiation potential at the places where monitoring stations are not established. The maximum mean absolute relative deviation of predicted hourly global radiation tested is 4.07%. Sozen *et al.* (2004a, 2004b) used an ANN for the estimation of the solar potential of Turkey based on geographical and meteorological data (latitude, longitude, altitude, month, mean sunshine duration, and mean temperature). To train the neural network, 3 year of the meteorological data (from 2000 to 2002) from 17 stations spread over Turkey were used as training (11 stations) and testing (6 stations) data. The maximum mean absolute percentage error was found to be less than 6.7% and the absolute fraction of variance (R^2) values to be about 99.9% for the testing stations. The trained and tested ANN models showed greater accuracies for evaluating solar resource possibilities in regions where a network of monitoring stations has not been established in Turkey. The predicted solar-potential values from the ANN were given in the form of monthly maps. In later development of these models, Sozen *et al.* (2005) used ANN to forecast the solar potential of Turkey, to train the neural network, meteorological data for 4 years

(2000–2003) and from 12 cities spread over Turkey were used in this study, nine stations as training and three stations as testing data.

Mellit *et al.* (2004a, 2004c) used the RBF networks for estimating total daily solar radiation in Algeria data from measured daily sunshine duration and temperature data. Soares *et al.* (2004) used a neural network for modeling the hourly diffuse solar radiation in the city of Sao Paulo, Brazil. In this work, a perceptron neural-network technique was applied to estimate hourly values of the diffuse solar radiation, using as input the global solar radiation and other meteorological parameters measured from 1998 to 2001. ANN verification was performed using the hourly measurements of the diffuse solar radiation obtained during 2002. The ANN was developed based on both feature determination and pattern selection techniques. The inclusion of the atmospheric long-wave radiation as input improves the neural network performance, while the inclusion of the traditional meteorological parameters, like air temperature and atmospheric pressure, are not as important as long-wave radiation which acts as a surrogate for cloud-cover information on the regional scale. An objective evaluation has shown that the diffuse solar radiation is better reproduced by neural network synthetic series than by a correlation model.

Hontoria *et al.* (2005a, 2005b) used a MLP technique for developing solar radiation maps for Spain. The inputs are the previous irradiation, clearness index and the hour order number of the K_T . Figure 10 shows the proposed ANN for clearness index prediction. To obtain a solar radiation map it is necessary to know the solar radiation of many points spread wide across the area where the map is going to be drawn. In most of the areas the data may not be available and even where there are data they may be affected by errors, data gaps, etc. In addition, to draw solar radiation maps the number of points on the maps (real sites) that it is necessary to work with makes this problem difficult to solve. However, once the

Figure 10. MLP architecture for clearness indexes prediction (Adapted from Hontoria et al., 2005a)

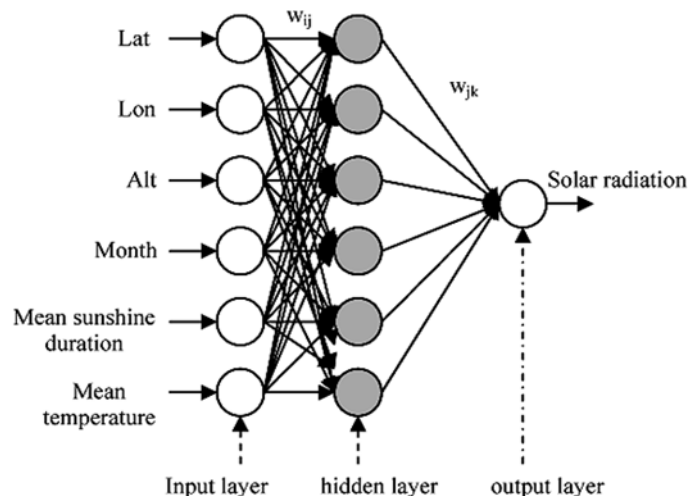


MLP is trained a solar generation can be done in all of the sites of the grid, which form the zone map. This generation is simple and takes less time than the same generation than classical methods of solar generation. Their methodology is easily extendible to other places.

A methodology for developing a simple theoretical model for calculating global insolation on a horizontal surface was proposed by Elminir et al. (2005). The input parameters to the model are

the latitude of the desired location and the amount of total precipitable water content in the vertical column at that location. Over the range of latitudes covering most parts of India, the error is within 20% of the measured value. An ANN based forecasting of the mean monthly solar radiation in Turkey was proposed by Adnan et al. (2005). The proposed model has as inputs the geographical coordinates, altitude, mean sunshine duration, mean temperature and month. According to the

Figure 11. A single hidden-layer ANN for prediction solar radiation (Adapted from Adnan et al., 2005)



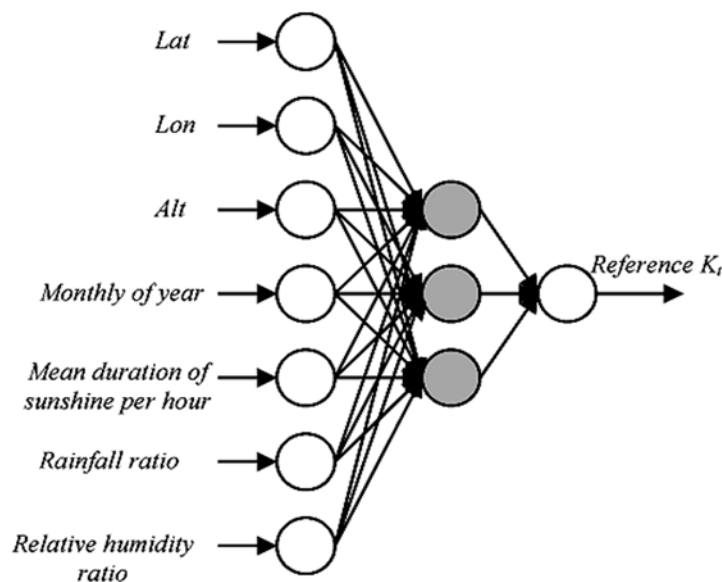
authors, the results indicate that the ANN model seems promising for evaluating solar resource potential at the places where there are no monitoring stations in Turkey. Figure 11 shows the proposed ANN for solar radiation forecasting. A comparative study of Angstroms and ANN methodologies in estimating global solar radiation on horizontal surfaces in Cyprus was developed by Tymvios *et al.* (2002, 2005). The ANN methodology is a promising alternative to the traditional approach for estimating global solar radiation, especially in cases where radiation measurements are not readily available.

Mellit *et al.* (2005b) proposed an ANN and Markov transitions matrices (MTM) for prediction of daily solar radiation and this model has been applied for sizing a PV system at isolated sites. The developed model can generate a sequence of global solar radiation data using a minimum of input data (latitude, longitude and altitude), especially in isolated sites. Using data collected at 60 meteorological stations in Algeria during 1991–2000, a data base and a typical meteorological year (TMY) have been built. A two steps methodology was constructed. First, a neural network has been trained based on 60 known

monthly solar radiation data from the TMY. The neural network can generate the monthly solar radiation data. Secondly, the data have been divided by corresponding extraterrestrial value in order to obtain the monthly clearness index values. Based on these monthly clearness indexes and using a library of MTM block the sequences of daily clearness indexes were generated. Known data were subsequently used to investigate the accuracy of the prediction. Results obtained indicate that the proposed model can successfully be used for the estimation of the daily solar radiation data for any locations in Algeria by using as input the altitude, the longitude, and the latitude. The model can be easily applied for any location in the world. An application of sizing PV systems in isolated sites has also been applied in order to check the model's validity.

López *et al.* (2005) proposed selection of input parameters to model direct solar irradiance, which is seldom measured by using an ANN and global solar radiation measurements. The proposed ANN methodology can be used in unfavorable conditions, in terms of limited amount of available data, performing successful results. In this work, the Bayesian framework for ANN, named as automatic

Figure 12. ANN model used for the estimation of beam solar radiation (Adapted from Alam *et al.*, 2006)



relevance determination method (ARD), was employed to obtain the relative relevance of a large set of atmospheric and radiometric variables used for estimating the hourly direct solar irradiance. In addition, the authors tested the viability of this novel technique applied to select the optimum input parameters to the neural network. For that, a multi-layer feed forward perceptron was trained on these data. The results reflect the relative importance of the inputs selected. Clearness index and relative air mass were found to be the more relevant input variables to the neural network, as it was expected, proving the reliability of the ARD method. The novel methodology can be used in unfavorable conditions, in terms of limited amount of available data, performing successful results. The model was tested using radiometric data measured at Desert Rock, USA, between 1989 and 1999. AI techniques, such as FL and neural networks, have been used for estimating hourly global radiation from satellite images (Zarzalejo and Ramirez, 2005). The models have been fitted to measured global irradiance data from 15 Spanish terrestrial stations.

Alam *et al.* (2006) proposed an ANN model for estimating beam solar radiation. A new defined parameter, known as Reference Clearness Index (RCI), is introduced. Computation of monthly mean daily beam solar radiation at normal incidence has been carried out. According to the authors, the results of the ANN model were compared with measured data based on Root Mean Square Error (RMSE) and Mean Bias Error (MBE). It was found that RMSE in the ANN model varies from 1.65% to 79% for the Indian region. Figure 11 shows the proposed ANN architecture used for estimating the beam solar radiation.

Elminir *et al.* (2007) proposed an ANN model to predict diffuse fraction in hourly and daily scale (K_D). An attempt was also done to describe the ANN outputs in terms of first order polynomials relating K_D with clearness index (K_T) and sunshine fraction (S/S_0). The procedure used here

was similar with one of (Zervas *et al.*, 2008). If care is taken in considering the corresponding regional climatic differences, these correlations can be generalized and transferred to other sites. A comparison between the performances of the ANN model with that of two linear regression models has been reported. The results show that the ANN model is more suitable to predict diffuse fraction in hourly and daily scales than the regression models in the plain areas of Egypt. Turbidity and water vapor, under cloudless conditions, are important source of variability of the luminous efficacy. Due to the complex functional relationship between these atmospheric variables and the luminous efficacy components, the derivation of an on-local model considering all these physical processes is nearly impossible if standard statistical techniques are employed.

To avoid this drawback, Iqdour and Zeronal (2006) developed a MLP model to predict daily solar radiation for Morocco. They applied Pollack-Ribiere algorithm to train the neural network. The agreement between the measured and predicted daily solar radiation was excellent (see Figure 13 for details). The model can be easily applied to other locations.

Lopez and Gueymard (2007) used ANN for clear-sky solar luminous efficacy of direct, diffuse, and global radiation estimates. In this purpose, a detailed spectral radiation model (SMARTS) is utilized to generate both illuminance and solar radiation values covering a large range of atmospheric conditions. Different input configurations using combinations of atmospheric variables and radiometric quantities were analyzed. Results presented in this paper shown that an ANN model using direct and diffuse solar irradiance along with precipitable water is able to accurately reproduce the variations of the three components of luminous efficacy caused by solar zenith angle and the various atmospheric absorption and scattering processes. The model developed in [46] is considerably simpler than the SMARTS radiation model it is derived from, but still can retain most

Figure 13. Measured and predicted daily radiation (Adapted from Iqdour and Zeronal, 2006)

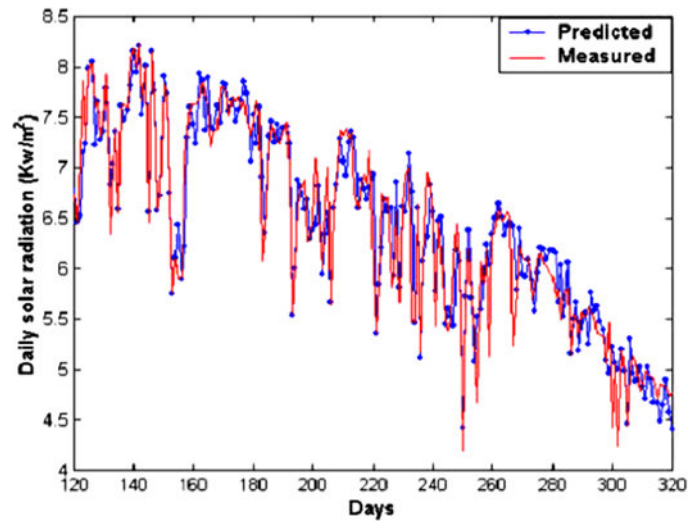
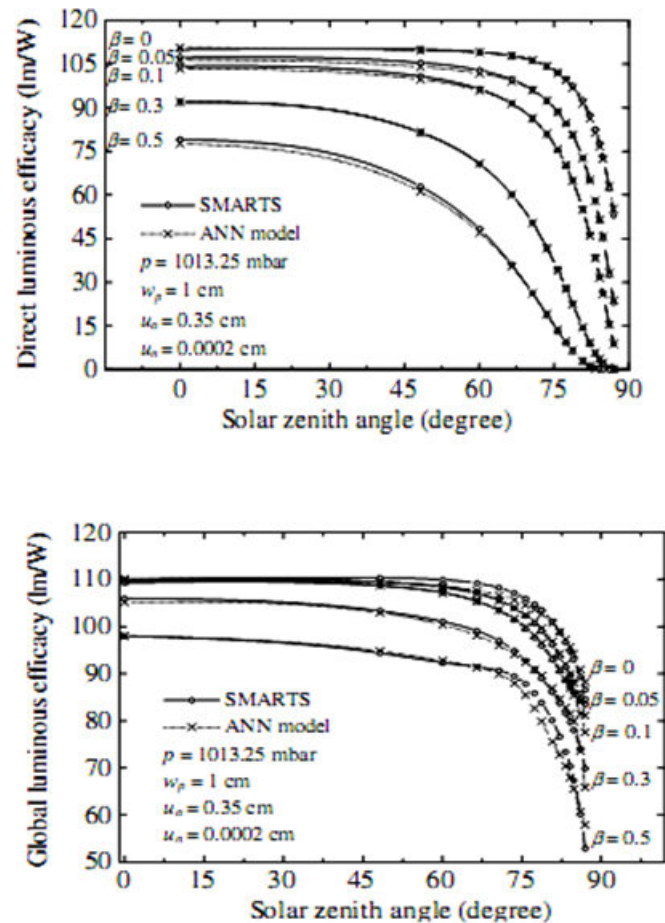


Figure 14. Luminous efficacy components predicted by the SMARTS and ANN models for different turbidity conditions (Lopez and Gueyamard, 2007, used with permission)



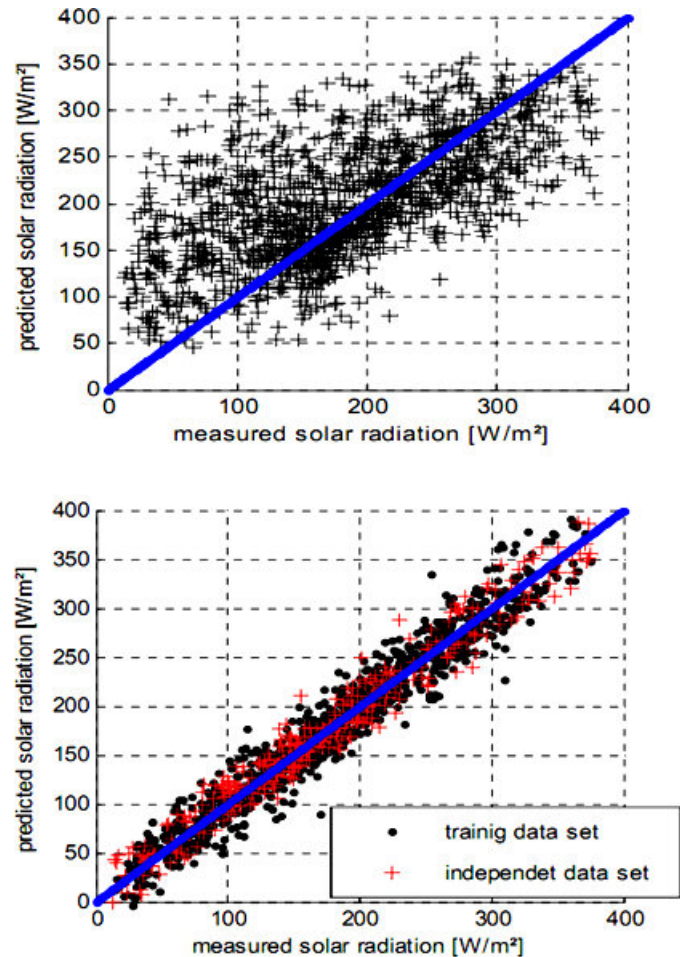
of its predicting power and versatility. The proposed ANN model can thus be used worldwide, avoiding the need of using detailed atmospheric information or empirical models if radiometric measurements and precipitable water data (or temperature and relative humidity data) are available. Figure 14 displays the luminous efficacy components predicted by the ANN model and SMARTS versus solar zenith angle, for different turbidity conditions. An excellent agreement between the two models was found in this study.

Mubiru and Banda (2008) used ANN for estimating the monthly average daily global solar irradiation on the horizontal surface in Uganda. He model estimated the averaged daily solar radiation by using weather station data: sunshine duration, maximum temperature, cloud coverage, and location parameters (latitude, longitude and altitude). The comparison between the ANN and empirical method emphasized the superiority of the proposed ANN prediction model. Kratzenberg *et al.* (2008) developed an ANN model to improve the performances of the Numerical Weather Prediction (NWP) model in forecasting daily solar radiation. The NWP models have very low forecast performance for the solar radiation. With the intent to increase the performance of these models, their output variables are corrected, traditionally with Model Output Statistic techniques. The NWP model residuals, the forecasted weather variable subtracted from the measured variable are estimated. Even the corrected solar radiation forecasts do presently not have satisfactory forecast performance. In this work the solar radiation is forecasted with the non-hydrostatic model Advanced Regional Prediction System. This model is providing its forecast weather variables for a horizontal grid of $(0.12 \times 0.12)^\circ$ resolution with a sampling interval of 10 min. In their approach a novel high performance MOS technique was developed, based on the Discrete Wavelet Transformation (DWT) and ANNs. The daily solar energy forecast by the presented method reduces the RMSE from 25.5% to 9.06% for the

site Florianopolis, localized in the subtropical south of Brazil. As shown in Figure 15 the presented ANN-based MOS model improves considerably the output of the ARPS model simulation.

Measured air temperature and relative humidity values, where used by Rehman and Mohandes (2008) for the estimation of the global solar radiation (GSR) in future time domain using artificial neural network method. The measurements used in this study were collected between 1998 and 2002 for Abha city in Saudi Arabia. The estimations of GSR were made using three combinations of data sets namely: (i) day of the year and daily maximum air temperatures inputs and GSR as output, (ii) day of the year and daily mean air temperatures inputs and GSR as output and (iii) time day of the year, daily mean air temperature and relative humidity as inputs and GSR as output. The measured data between 1998 and 2001 were used for training the neural networks while the remaining 240 days' data from 2002 as testing data. The testing data were not used in training the neural networks. Obtained results are showing that neural networks are well capable of estimating GSR from temperature and relative humidity. This can be used for estimating GSR for locations where only temperature and humidity data are available. A in depth and comprehensive review of the AI technique applications was published by Mellit (2008). In this paper the author presents an overview of AI techniques for modeling, prediction and forecasting of solar radiation data. Published literature works, up to 2008 is presented and the potential of AI as a design tool for prediction and forecasting of solar radiation data is discussed. Additionally, the advantages of using AI-based prediction solar radiation data in isolated areas where there no instrument for the measurement of this data, especially the parameters related to photovoltaic (PV) systems is also discussed. Interested reader also can find a rich bibliography in the Mellit and Kalogirou (2008) review paper.

Figure 15. Daily mean values of the forecasted versus the ground measured global solar radiation on horizontal surface utilizing the ARPS model (left panel) and the ANN-based model (right panel) (Adapted from Kratzenberg et al., 2008)



Jiang (2008) developed an artificial neural network (ANN) model for estimating the monthly mean daily diffuse solar radiation. Solar radiation data from 9 stations having different climatic conditions all over China were used in this study. Data, collected during 1995–2004 were used for training and testing the ANN. Solar radiation data from eight typical cities are used for training the neural networks, while the data from the remaining one location was used for testing the estimated values. Estimated values were compared with measured values in terms of mean percentage error (MPE), mean bias error (MBE) and root

mean square error (RMSE). The results of the ANN model have been compared with empirical regression models to further test the ANN model. A feed-forward back-propagation algorithm with single hidden layer was used in this analysis. The input variables are: the monthly mean daily clearness index, and sunshine percentage, while the output is monthly mean daily diffuse fraction. The solar radiation estimations by ANN are in good agreement with the actual values and are superior to those of other available models. In addition, ANN model was tested to predict the same components for Zhengzhou station over the

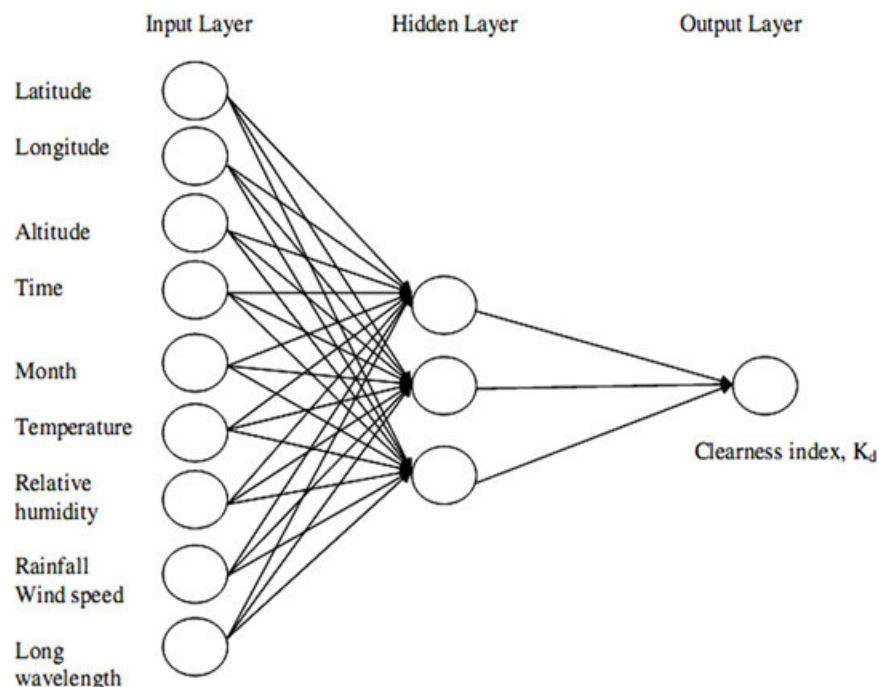
same period. Results indicate that ANN model predicts the actual values for Zhengzhou with a good accuracy of 94.81%. Data for Zhengzhou are not included as a part of ANN training set. Hence, these results demonstrate the generalization capability of this approach and its ability to produce accurate estimates.

The hourly solar radiation data collected during the period August 1, 2005 July 30, 2006 from the solar observation station in IkiEylul campus area of Eskisehir region of Turkey was used by Hocaoglu et al (2008) in a 2-D representation model of the hourly solar radiation estimates. The model provides a unique and compact visualization of the data for inspection, and enables accurate forecasting using image processing methods. Using the hourly solar radiation data mentioned above, the image model formed in raster scan form with rows and columns corresponding to days and hours, respectively. The results provide the necessary correlation model and prediction directions for obtaining the optimum prediction template for

forecasting. The 2-D forecasting performance is tested through feed forward neural networks using the same data. The optimal linear filters and ANN models are compared in the sense of root mean-square-error (RMSE). An ANN based model was used by Boscha *et al.* (2008) to interpolate daily solar radiation over the complex terrain in Spain. Zervas *et al.* (2008) developed a ANN prediction model of the global solar irradiance distribution on horizontal surfaces. The approach was based on neural network techniques and has been applied to the meteorological database of NTUA Campus, Athens, Greece.

Alam *et al.* (2009) used ANN models for estimating monthly mean hourly and daily diffuse solar radiation. Solar radiation data from 10 Indian stations, having different climatic conditions, all over India have been used for training and testing the ANN model. The coefficient of determination (R^2) for all the stations are higher than 0.85, indicating strong correlation between diffuse solar radiation and selected input parameters. The feed

Figure 16. ANN architecture for the prediction of diffuse solar radiation (Adapted from Alam *et al.*, 2009)



forward back-propagation algorithm was used in this analysis (see Figure 16). The neurons in the input layer receive nine input signals representing the latitude, longitude, altitude, time, month of the year, air temperature, relative humidity, rainfall, wind speed and net long wavelength. The output layer consists of one output neuron representing the diffuse solar radiation that is clearness index, K_d . Results of ANN models have been compared with the measured data on the basis of percentage root-mean-square error (RMSE) and mean bias error (MBE). The maximum value of RMSE in

ANN model is 8.8% in the prediction of hourly diffuse solar radiation. The computation of monthly mean daily diffuse solar radiation was also carried out and the results were compared with those of other empirical models. The ANN model shows the maximum $RMSE$ of 4.5% for daily diffuse radiation, while for other empirical models the same error is 37.4%, proving that the ANN model performs better than empirical counterparts.

An ANN-based model for prediction of solar energy potential in Nigeria was developed by Fadare (2009). Standard multi-layered, feed-forward, back-propagation neural networks with different architecture designed using neural toolbox for MATLAB were used in this study. Geographical and meteorological data of 195 cities in Nigeria for period of 10 years (1983-1993) and from the NASA geo-satellite database were used for the training and testing the network. Meteorological and geographical data (latitude, longitude, altitude, month, mean sunshine duration, mean temperature, and relative humidity) were used as inputs to the network, while the solar radiation intensity was the output of the network. The results shown that the correlation coefficients between the ANN predictions and actual mean monthly global solar radiation intensities for training and testing data sets were higher than 90% suggesting a high reliability of the model for evaluation of solar radiation in locations where solar radiation data are not available. The predicted solar radia-

tion values from the model were given in form of monthly maps. Azadeh et al (2009) developed an integrated ANN model for predicting solar global radiation by using climatological variables, as inputs. The proposed approach is particularly useful for locations where no available measurement equipment.

Seme et al (2009) was studied the prediction of solar irradiation during the day. In order to predict half hourly solar irradiation during the day an artificial neural network is applied. The artificial neural network was trained using error back-propagation learning rule. Meteorological data measured during three years in Slovenia were used to form learning patterns. The trained artificial neural network was tested with different patterns. Some of them were new while the others were used in the training procedure. The comparison of measured and by the artificial neural network predicted daily distribution of solar irradiation shows a very good agreement for the clear days. Mehleri et al (2009) performed extensive comparisons of various hourly slope irradiation models, found in the literature, in order to select the most accurate for the region of Athens. Finally, a neural network model was developed to predict the global solar irradiance on a tilted surface, using as input data the total solar irradiance on a horizontal surface, the extraterrestrial radiation, the solar zenith angle and the solar incidence angle on a tilted plane. The comparison with the aforementioned models has shown that the neural network model, predicts more realistically the total solar irradiance on a tilted surface, as it performs better in regions where the other models show under estimation or over estimation in their calculations.

Rahimikhoob (2010) tested an ANN model for the estimation of the global solar radiation as a function of air temperature data in a semi-arid environment. The ANNs (multilayer perceptron type) were trained to estimate GSR as a function of the maximum and minimum air temperature and extraterrestrial radiation. The data used in the network training were obtained from a historical

series (1994–2001) of daily climatic data collected in weather station of Ahwaz located in Khuzestan plain in the southwest of Iran. ANN-based models for forecasting GSR on horizontal surfaces were also developed and tested against conventional/empirical GSR prediction models by Behrang et al (2010). Daily mean air temperature, relative humidity, sunshine hours, evaporation, and wind speed values collected between 2002 and 2006 for Dezful city in Iran, were used in this study.

In order to consider the effect of each meteorological variable on the daily GSR prediction (the model output), six combinations of the input variables were analyzed: a) day of the year, daily mean air temperature and relative humidity; b) day of the year, daily mean air temperature and sunshine hours; c) day of the year, daily mean air temperature, relative humidity and sunshine hours; d) day of the year, daily mean air temperature, relative humidity, sunshine hours and evaporation; e) day of the year, daily mean air temperature, relative humidity, sunshine hours and wind speed; and f) day of the year, daily mean air temperature, relative humidity, sunshine hours, evaporation and wind speed. Multi-layer perceptron (MLP) and radial basis function (RBF) neural networks are applied for daily GSR modeling based on the six proposed combinations of the input variables. The measured data between 2002 and 2005 were used to train the neural networks, while the data for 214 days from 2006 were used to test the models. The comparison of obtained results from ANNs and several conventional GSR prediction (CGSRP) models is shown higher performances of the ANN-based models over the empirical ones. The MLP architecture with day of the year, daily mean air temperature, relative humidity, sunshine hours and wind speed as inputs has the highest accuracy of predictions, while the RBF model with day of the year, daily mean air temperature and sunshine hours, as inputs also is showing a good accuracy.

FUZZY LOGIC AND HYBRID APPROACHES TO MODEL AND PREDICT SOLAR RADIATION

Sen (1998) used a FL approach for estimating solar radiation from sunshine duration measurements. A fuzzy logic algorithm for estimating the solar irradiation from sunshine duration measurements was proposed in this study. The main advantage of fuzzy models is their ability to describe the knowledge in a descriptive human-like manner in the form of simple rules using linguistic variables only. In this manner the classical Angstrom or any other type of regression equations can be replaced by a set of fuzzy rule bases. The fuzzy approach was applied to predict solar irradiance for three sites with monthly averages of daily irradiances located in the western part of Turkey. The application of the proposed fuzzy subsets and rule bases is straightforward and easily to implement for any of the irradiation and sunshine duration measurements in any part of the world. Santamouris et al (1999) developed three methods for analyzing and modeling the global short wave radiation reaching the earth's surface. The estimation methods consist of an atmospheric deterministic model and two data-driven intelligent methods. The deterministic method is a broad band atmospheric model, developed for predicting the global and diffuse solar radiation incident on the earth's surface. The intelligent data-driven methods are a new neural network approach in which the hourly values of global radiation for several years are calculated and a new fuzzy logic method. The two data-driven models, calculating the global solar radiation on a horizontal surface, are based on measured data of several meteorological parameters such as the air temperature, the relative humidity, and the sunshine duration. The three methods were tested and compared using various sets of solar radiation measurements collected at Athens, Greece. The comparison of the three methods showed that the proposed intelligent techniques can be successfully used for the estimation of global solar

radiation during the warm period of the year, while during the cold period the atmospheric deterministic model gives better estimations.

A fuzzy model of solar irradiance on inclined surfaces has been developed by Gautman and Kaushika (2002). The fuzzy model includes concepts from earlier models, though unlike these, it considers non-disjunctive sky categories. The proposed model offers performance similar to that of the models with the best results in the comparative analysis of the literature, such as the Perez model. The cloudiness index is defined, in this study as the fraction of extraterrestrial radiation that reaches the earth's surface when the sky above the location of interest is obscured by the cloud cover. The cloud cover at the location of interest during the j th time interval of a day is assumed to follow the fuzzy random phenomenon. The cloudiness index, therefore, is considered, here as a fuzzy random variable that accounts for the cloud cover at the location of interest during the j th time interval of a day. A fuzzy based evaluation model of the quality of the performance of the solar radiation models was proposed by Bellocchi et al (2002). Three modules were formulated reflecting the magnitude of residuals (Accuracy), the correlation estimates and measurements (Correlation), and the presence or absence of patterns in the residuals against independent variables (Pattern), respectively. The Accuracy and Pattern modules resulted from the aggregation of three (relative root mean square error, modeling efficiency, and t -Student probability) and two (pattern index vs. day of the year and pattern index vs. minimum air temperature) indices, respectively, while the Correlation module was identified by a single index (Pearson's correlation coefficient). For each index, two functions describing membership to the fuzzy subsets Favorable (F) and Unfavorable (U) have been defined. The expert system calculates the modules according to both the membership degree of the indices to the subsets F and U and decision rules set. Then the modules are aggregated into the indicator I_{rad} . Sensitivity analysis

is presented, along with module and I_{rad} scores for some cases.

Solar irradiance is an extreme case of an uncertain variable when measured on an hourly or shorter time interval. Gomez and Casanovas (2002) proposed a suitable model for estimating the solar radiation data using FL random variables. The solar irradiance uncertainty is treated in this study as a fuzzy uncertainty whilst other variables are considered crisp. This approach is robust as it does not rely on statistical assumptions, and it is a possible alternative to modeling complex systems. This was one of the first attempts, proposed to use a physical model of a meteorological variable based on fuzzy numbers. Previous rule-based fuzzy meteorological models were only descriptive, and cannot be extrapolated to non-measured cases. Compared with previous non-fuzzy models of solar irradiance, this fuzzy model shows an improved performance, and when compared with experimental data, the performance can be evaluated by fuzzy indices that take into account the uncertainty of the data and the model output. Gomez and Casanovas (2003) proposed an updated model of the previous one for estimating solar irradiation based on FL, according to the authors the fuzzy model shows an improved performance, and when compared with experimental data.

Sen *et al.* (2004) developed a more efficient model based on the fuzzy system architecture for solar irradiation estimation from the sunshine duration measurements than the conventional empirical methods. Partial fuzzy modeling accounts for the possible local nonlinearities in the form of piece-wise linearization in this model. The parameters estimation of such a fuzzy model is achieved through the application of genetic algorithm technique. The fuzzy part of the model provides treatment of vague information about the sunshine duration data whereas the genetic part furnishes an objective and optimum estimation procedure. The application of genetic-fuzzy model as proposed in this article is presented for three

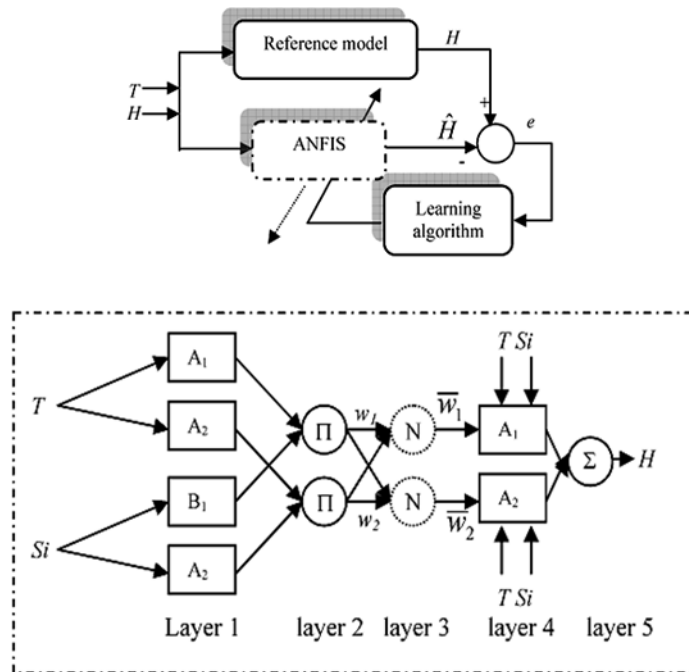
stations in Turkey and the results are compared by ones from the previous classical approaches. Rivington *et al.* (2006) conducted an extensive evaluation of three models for the solar radiation estimates, using data collected at 24 weather stations in the UK. Comparisons were made using a fuzzy-logic based multiple-indices assessment system (*Irada*) and tests of the temporal distribution of mean errors. The conversion from sunshine duration to solar radiation produces the best overall estimates, but shows systematic seasonal errors. The two air temperature based methods, discussed in this study can be reliable alternatives when only air temperature data are available. Their study demonstrates the value and importance of using a range of assessment methods to evaluate model estimates.

Lah *et al.* (2006) applied fuzzy logic approach to control and model daylight illuminance, Iqdour and Zeronal (2006) proposed the investigation of the use the fuzzy systems of Takagi Sugeno (TS) for modeling the daily solar radiation data. The Takagi-Sugeno models are non-linear techniques, defined by a set of If- Then rules, each of which establishes a local linear input-output relationship between the variables of the model. The TS fuzzy model is trained using data of daily solar radiation recorded on a horizontal surface in Dakhla in Morocco. The predicting results indicate that the Takagi-Sugeno fuzzy model gives a good accuracy of 96% and a root mean square error lower than 6%. In addition, the performances of the identified TS fuzzy model are then compared to a linear model using the SOS techniques. The results show the effectiveness of the nonlinear model. Paulescu *et al.* (2008) studied two models for solar radiation attenuation in the atmosphere. The novelty consists in using fuzzy logic algorithms for evaluating atmospheric transmittances associated to the main attenuators: Rayleigh scattering, aerosol extinction, ozone, water vapor and trace gas absorption. The first model encompasses self-dependent fuzzy modeling of each characteristic transmittance, while the second one is a proper fuzzy

logic model for beam and diffuse atmospheric transmittances. The results lead to the conclusion that developing parametric models along the ways of fuzzy logic is a viable alternative to classical parameterization. Due to the heuristic nature of the fuzzy model input-output map, it leads to more flexibility in adapting to local climatic conditions. Tulcan-Paulescu and Paulescu (2008) developed a model for estimating daily global solar irradiation from daily average air temperature based on the Fuzzy sets theory for locations in Romania. In addition to the presentation of a new mapping technique, from the input to the output of the model, an innovative approach for the tuning of the fuzzy algorithm to fit a local meteo-climate is proposed. Since air temperature-based solar radiation models are strongly dependent on the origin location, the adaptive method presented here is designed as a tool for potential users to either increase the application area or to devise more precise local models. A critical assessment of fuzzy model performances and limitations has been conducted. The reported results demonstrated the potential of modeling solar irradiation using the fuzzy sets approach.

A Neuro-Fuzzy approach has been developed for prediction of clearness index (K_t) in isolated sites for Algeria (Mellit and Guessoum, 2006). The inputs of this model are the geographical coordinates and the outputs are the mean monthly K_t . An adaptive ANN and hybrid models for prediction of daily solar radiation is proposed by Mellit *et al.* (2004d, 2007a). The models combine ANN and fuzzy logic (ANFIS). The input of these models is the mean temperature and the sunshine duration. Figure 17 illustrates the proposed ANFIS-model. Mellit *et al.* (2007b) proposed a new model based on neuro-fuzzy for predicting the sequences of monthly clearness index and proposed it for generating solar radiation, which has been used for the sizing of a PV-system. The authors proposed a hybrid model for estimating sequences of daily clearness index by using an ANFIS and Markov chain; the proposed model has been used for

Figure 17. The ANFIS-model used for estimating the irradiation from the mean temperature and the sunshine duration (Adapted from Mellit *et al.*, 2007a)

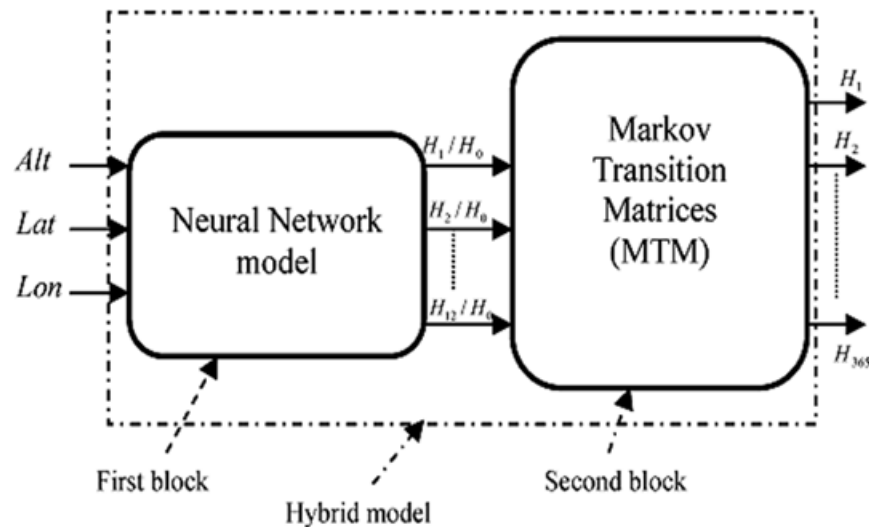


estimating the daily solar radiation. An application of sizing a PV-system is presented based on the data generated by this model. Badran *et al* (2009) studied study the use of the fuzzy logic to assess solar sites in Jordan and to decide which sites should be given the highest priority with respect to their benefits and costs. The criterion of evaluation using fuzzy logic is based on different parameters, i.e., solar resources, site capacity, site accessibility, soil condition, water availability, grid connection distance, land cost, land roughness, and wind speed. This method seems very promising for the solar site assessments.

APPLICATION OF NEURAL NETWORKS AND MARKOV CHAINS FOR SOLAR RADIATION PREDICTION

Mellit *et al.* (2004c, 2005b, 2005c) proposed simplified hybrid models for generating sequences of total daily solar radiation; the proposed model combines neural networks and Markov chains. This model is called the ANN-MTM (Markov Transition Matrix). The inputs of the proposed model are the geographical coordinates while the outputs are the daily total solar radiation. It can be used for generating sequences of solar radiation in the long term and it was applied for Algeria. Figure 18 shows the hybrid configuration for generating sequences of daily solar radiation data. Cao and Cao (2005) developed a hybrid model for forecasting sequences of total daily solar radiation, which combines ANN with wavelet analysis. The characteristic of this method is the pre-processing

Figure 18. Block diagram of hybrid model ANN–MTM (Adapted from Mellit et al., 2005b)



of data using wavelet transformation, i.e., the data sequence of solar irradiation is first mapped onto several time-frequency domains and then a recurrent Back-Propagation (BP) network is established for each domain. According to the authors, the results showed that the accuracy of the method is more satisfactory than that of the methods reported before (see Figure 18 for details).

Mellit (2006) also proposed an ANN with Discrete Wavelet Transforms (DWTs) for time series prediction. This model has been used for prediction of solar radiation based on sunshine duration and mean temperature. Cao and Cao (2006) used neural network and wavelet analysis for prediction of solar radiation. Mellit *et al.* (2006) proposed an adaptive wavelet-network model for forecasting daily total solar radiation. In this study, several structures have been investigated for resolving the missing data problem. In this particular estimation process, the model consists of an adaptive neural-network topology with the wavelet transformation embedded in the hidden units. The IIR synopsis network is used to create a ‘double’ local network architecture that provides a computationally efficient method of training the

system and results in quick learning and fast convergence.

An ANN fuzzy logic assisted model to forecast solar irradiance was proposed by Cao and Lin (2008). In general, the forecast models based on ANN perform much better in accuracy than many conventional prediction models. However, a fact could not be neglected that most of such existing ANN-based models have not yet satisfied researchers and engineers in forecast precision so far, and the generalization capability of these networks needs further improving. Combining the prominent dynamic characteristics of recurrent neural network with the enhanced ability of wavelet neural network (WNN) in mapping nonlinear functions, the authors proposed a diagonal recurrent wavelet neural network (DRWNN) method to carry out fine forecasting of the hourly global solar irradiance. Some additional steps, e.g., using fuzzy technique to apply historical information of cloud cover to sample data sets for network training and the forecasted cloud cover in weather program to network input for the irradiation forecasting, were also adopted to help enhancing forecast precision. The hourly irradiance forecast is completed using the sample data

set in Shanghai, China and comparisons between irradiation models show that the DRWNN model is definitely more accurate.

CONVENTIONAL METHODS FOR PV SYSTEM SIZING

Power output of a solar energy system varies according to the irradiation and global system functioning conditions. In any solar energy and PV system, sizing represents an important part of the system design. The optimal selection of the number of solar cell panels, collector selection, the size of the storage battery and the size of wind-generator to be used for certain applications at a particular site is an important economical task for electrification of villages in rural areas, telecommunications, refrigeration, water pumping, and water heating, etc. Besides being an economic waste, an oversized system can also adversely affect further utilization of the solar cells and the pollution-free PV energy. The estimation of the sizing parameters PV-array area, useful capacity of battery, wind generator is very useful to conceive an optimal PV systems as well as conceiving an optimal and economic PV systems particularly in isolated sites (Sahara regions, small island archipelagos, remote areas in developing nations, mountainous locations, rural regions, etc.). In order to decide the size of any solar energy conversion system, especially of the stand-alone photovoltaic system, various methods can be used. Over the years, several models have been developed, simulating and sizing PV systems using different operation strategies. Some are more accurate than others and range from those known as intuitive to others in which a detailed simulation and analysis methods of the system is carried out (numerical methods). Somewhere between these two poles are the analytical methods that sacrifice certain accuracy in order to gain simplicity in the calculations. Among these methods, there are ones proposed, more than three decades by Barra et al (1984), Bartoli *et al.* (1984), and Egido

and Lorenzo (1992). In all of these, accuracy is achieved by using data from daily global irradiation series. If this kind of data is not available, the loss of accuracy is significant, or the method cannot be used. Sidrach-de-Cardona and Mora Lopez (1999) suggested an alternative method: a multivariate qualitative model is proposed to calculate the size of the stand-alone PV system, using as input mean monthly irradiation values and setting parameters.

The estimation of the excess of energy provided by PV generators using the utilisability method was developed by Liu and Jordan (1977). The excess energy provided by PV systems for an installation having a constant load was also evaluated by Klein (1978). Siegel *et al.* (1981) evaluated the monthly average output, the excess of energy and the storage capacity of the batteries. Evans et al (1981) described a method to consider the monthly average output of PV fields. All these methods are based on the energy balance of the systems studied to determine their storage capacity and output. In the so-called numerical methods employed to calculate the size of the PV system for the various sites are based on the loss of load probability method (LOLP). The data obtained with this method is usually processed via multivariate regression linear analysis. The LOLP method is based on the ideas proposed by Gordon (1981), and Klein and Beckman (1987). LOLP is defined as the dimensionless energy deficit, for a PV system, carried out over a sufficiently long period of time which allows us to fully characterize the statistical nature of the solar irradiation. To determine the array capacity and the battery sizes for a specified LOLP, the long-term photovoltaic behavior has been simulated and calculated daily. The first step in this method is to calculate the solar irradiation incident on the tilted surface, employing one of the methods presented in the previous sections of this chapter. In order to simulate the behavior of a PV system, a daily energy balance is carried out each day

Other methods used to estimate the performance of PV systems are based on the Loss of Load Probability (LLP) technique, defined as the ratio between the energy deficit and the energy demand, both on the load, there are developed by Bucciarelli (1984), Klein and Beckman (1987), Barra *et al.* (1994), and by Bartoli *et al.* (1984). These analytical methods are simple to apply but they are not general. On the other hand, the numerical methods presented by Bucciarelli (1984), Groumpos and Papageorgiou (1987), Graham *et al.* (1988), Aguiar *et al.* (1988), Chapman (1990) and Abouzahr (1991) present a good solution, but these need a long period solar radiation data record. Egido and Lorenzo (1992) reviewed methods for computing capacity of PV arrays and battery storage and suggested analytical model based on LOLP, where it uses more complex methods which allow the improvement of the precision of the LLP calculation according to the dimension of the PV-array area and the storage capacity. An optimal method for the panel area of PV system in relation to the static inverter practical results has been developed by Keller and Affolter (1995). A detailed evaluation of the sensitivity of a numerical sizing method developed by Notton *et al.* (1996), has shown that the influences of some parameters on the sizing, i.e., simulation time step, input and output power profile are very important. It is therefore important to have knowledge of the daily profile at least on an hourly basis. The authors have highlighted that optimal solution can be obtained if PV contributes for 75% of the energy requirements.

The cost of electricity generated from a hybrid PV system is also one of the decision-making parameters. Shrestha and Goel (1998) demonstrated a method to find optimal combination of PV array size and battery to meet the refrigeration load, by using statistical models for both solar radiation and the load. Mellit *et al.* (2005, 2008) developed methods to design stand-alone PV systems, for remote areas of Algeria based on mean monthly clearness index and daily solar radiation data.

Benghanem (2002) has been developed a suitable methodology based on LLP for sizing PV-system in Algeria. Bhuiyan and Asgar (2003) optimized PV battery system for Dhaka, Bangladesh with respect to power output for different tilt and azimuth angle for optimum performance of the system. Mellit *et al.*, (2004c) have presented a simplified methodology for optimal sizing PV-system in Algeria based on spatial interpolation method. Kaushika *et al.* (2005) developed a computational scheme for stand-alone solar PV systems with interconnected arrays have been investigated for optimal sizing of the array and battery bank. The loss of power supply probability (LPSP) is used to connote the risk of not satisfying the load demand.

At the beginning of the 1990's, the main PV applications were stand-alone PV system applications. However, PV grid-connected systems (PVGCS) have had the largest growth since 2000. In fact, PVGCS residential applications are estimated to have risen. Grid-connected applications are the fastest growing segment of the photovoltaic (PV) market with premium feed-in tariffs available in many countries. Peippo and Lund (1994) have proposed an optimal ratio of the nominal PV-array capacity to the rated inverter input capacity in PVGCS based on numerical simulations for several locations. Keller *et al.*, (2005) have developed a methodology for solving the problem of poor sizing. PVGCS systems often under exploit the capacity of the static inverter resulting in reduced efficiency and an increase in the cost of energy. A simple process for the evaluation of the optimal size of grid-PV-generator in building has been developed (Hernandez *et al.* 2007) and has been used as a useful tool for the PV designer in the choice of sizing the PV system capable for supplying the maximum building electricity consumption with a minimum cost. Optimum PV/inverter sizing ratios for PVGCS in selected European locations were determined in terms of total system output, system output per specific cost of a system, system output per annualized specific cost of a system, has been described (Burger and

Ruithier, 2006). In (Mellit *et al.* 2003) the authors have discussed how the time resolution of solar radiation data influences the correct sizing of PV plants. And they have demonstrated that using instant (10 s) irradiation values instead of average hourly irradiation values leads to considerable differences in optimum inverter sizing.

AI TECHNIQUES FOR SEIZING PV SYSTEMS

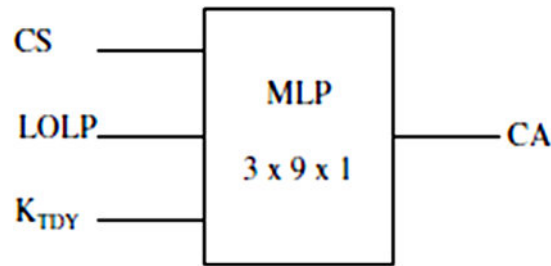
The conventional methodology (empiric, analytic, numeric, hybrid, etc.) for sizing PV-systems have been used for a location where the required weather data (irradiation, temperature, humidity, clearness index, wind speed, etc.) and the information concerning the site where we want to implement the PV system are available. In this case these methods present a good solution, particularly hybrid method for sizing PV-systems. However, these techniques could not be used for sizing PV systems in remote areas, in the case where the required data are not available. Moreover, the major of the above methods need the long term meteorological data such as total solar irradiation, air temperature, wind speed, etc. for its operation. So, when the relevant meteorological data are not available, these methods cannot be used, especially in the isolated areas. In order to overcome this situation, more recent methods have been developed in the literature for sizing parameters for PV-systems based on AI-techniques (Mellit *et al.* 2003, 2004a, 2004b, 2004e, 2005a, 2006). A comprehensive overview of the application of AI techniques in the PV-systems sizing is presented in next subsections of this chapter.

Conti et al (2002) proposed one of the first applications of the AI techniques in the PV system sizing. It consists of an automatic procedure to perform the optimal sizing of a stand-alone solar electrical system with battery storage is developed by a FL based multi-objective optimization approach. The procedure aims at finding

the configuration that yields the best compromise for the two considered objectives: the long-term average performance and the overall cost of the generating system. In particular, the objectives of the optimization problem are: the maximization of the Supplied Load Fraction, that is the fraction of the actual electrical load that can be supplied by the system, and the minimization of the Relative Unit Electricity Cost, that is the net cost of generating each kWh during the lifetime of the stand-alone solar electrical system referred to the UEC calculated in case of loads supplied by the grid. The control variables are the solar cell array surface, the tilt angle of the modules, and the storage system capacity. The fuzzy multi-objective optimization procedure is described and the application results are presented considering different configurations characterized by some parameters, such as the electrical load, the yearly power demand, the distance from the utility grid, and the solar cells unit cost.

Mellit *et al.* (2003) studied the application of an ANN model for the estimation of the sizing parameters of stand-alone PV-systems. In this model, the input parameters are the latitude and longitude of the site, while the outputs are two hybrid-sizing parameters. These parameters are used by the designers of PV-systems to determine the number of PV modules and the storage unit capacity necessary to satisfy a given consumption. While Mellit *et al.* (2004a) used RBF architecture to identify and model the optimal sizing of a stand-alone PV system. The results have been compared and tested with experimental values in these applications. An application to sizing of stand-alone PV systems was developed by Mellit et al (2004a). These optimal sizing combinations allow to the users of stand-alone PV systems to determine the number of solar panel modules and storage batteries necessary, to satisfy a given consumption, especially in isolated sites where the global solar radiation data is not always available. A developed model combines a Multi-Layer Perceptron (MLP), wavelets and infinite impulse

Figure 19. MLP architecture for the obtaining of the LLP curves (Adapted from Hontoria et al. 2006)

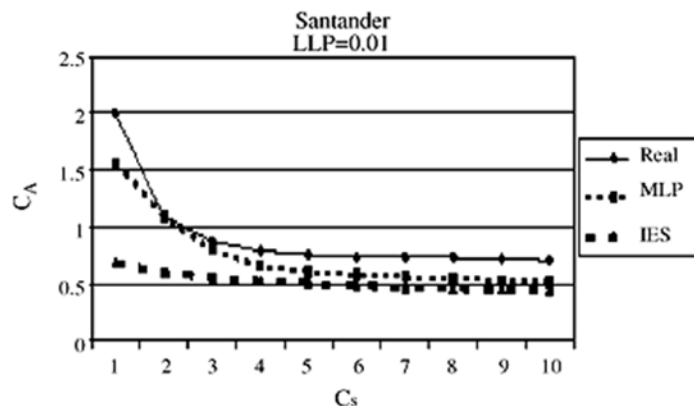


response (IIR) filter. The wave-net model has been trained by using 200 known sizing coefficients data corresponding to 200 locations. In this way, the adaptive model was trained to accept and even handle a number of unusual cases. Known sizing coefficients were subsequently used to investigate the accuracy of estimation, the unknown validation sizing coefficients set produced very accurate estimation with the correlation coefficient between the actual and the wave-net model estimated data of 98% was obtained. This result indicates that the proposed method can be successfully used for estimating of optimal sizing coefficients of the stand-alone PV systems, not only for any locations in Algeria, but the methodology can be easily generalized for other areas.

Hontoria *et al.* (2006, and 2007) developed a suitable technique for drawing the iso-reliability

curves by using simplified recurrent neural networks. This technique has been applied for Spanish locations. Figure 19 presents the architecture used for this simulation. It consists of three layers. The input layer has three inputs which are the following ones: the accumulator capacity (CS), defined as the maximum energy that can be extracted from the accumulator divided by the average daily consumption of the load; loss of load probability (LOLP); and yearly clearness index (K_{TDY}). The output of the MLP is the generator capacity (CA), which is defined as the ratio of the average energy output of the generator in the month with worst solar radiation input divided by the average consumption of the load (assuming a constant consumption of load for every month). Figure 20 shows an example of generated curve by MLP, for Santander location, for a LLP=0.01.

Figure 20. LLP curves obtained by different methods (Santander, LLP=0.01) (Adapted from Hontoria et al., 2006)



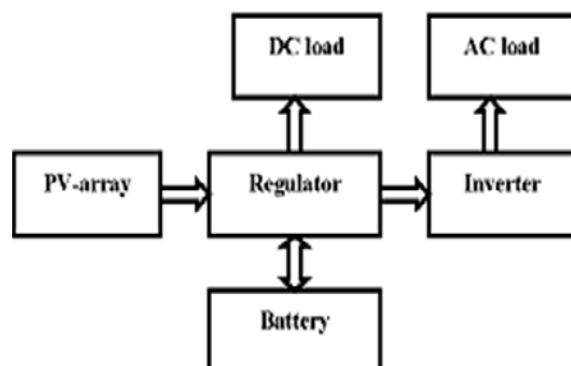
Several AI-based methods for sizing PV systems have been developed by several authors in order to select the optimal size of parameters of PV systems in remote areas. The results obtained have been compared and tested with experimental data. Mellit *et al.* (2004) developed a suitable approach, which combines the ANN with wavelet analysis for the sizing of stand-alone PV system. The proposed approach presents more accurate results compared with MLP, RBF and RNN. Mellit *et al.* (2005) investigated the of RBF networks to find a model for daily global solar radiation data from sunshine duration and air temperature. This methodology is considered suitable for prediction time series, by using the database of daily sunshine duration, air temperature and global solar radiation data corresponding to Typical Reference Year (TRY). A RBF model has been trained based on 300 known data from TRY, in this way, the network was trained to accept and even handle a number of unusual cases. Known data were subsequently used to investigate the accuracy of prediction. Subsequently, the unknown validation data set produced very accurate estimation, with the mean relative error (MRE) not exceed 1.5% between the actual and predicted data, also the correlation coefficient obtained for the validation data set is 98.9%, these results indicates that the proposed model can successfully be used for prediction and modeling of daily global solar radiation data from sunshine duration and air temperature. An application for sizing of stand-alone PV system has been presented in this paper in order to shows the importance of this modeling.

Mellit and Kalogirou (2006) proposed a methodology for modeling of a Photovoltaic Power Supply (PVPS) system using an Adaptive Neuro-fuzzy Inference System (ANFIS). For the modeling of the PVPS system, it is required to find suitable models for its different components (ANFIS PV-generator, ANFIS battery and ANFIS regulator) under variable climatic conditions. A simple configuration of PVPS-system is shown

in Figure 21. A database of measured weather data (global radiation, temperature and humidity) and electrical signals (photovoltaic, battery and regulator voltage and current) of a PVPS system installed in Tahifet (southern Algeria) has been recorded for the period from 1992 to 1997 using a data acquisition system. These data have been used for the modeling and simulation of the PVPS system. The ANFIS for the PV-generator, battery and regulator have been trained by using 10 signals recorded from the different components of the PVPS system. A set of data for 4-years have been used for the training of the ANFIS and data for 1-year has been used for the testing of the ANFIS. The ANFIS was trained to accept and handle a number of unusual cases. The comparison between actual and estimated values obtained from the ANFIS gave satisfactory results. The correlation coefficient between measured values and those estimated by the ANFIS gave good prediction accuracy of 98%. In addition, test results show that the ANFIS performed better than the ANN models. Predicted electrical signals by the ANFIS can be used for several applications in PV systems.

Mellit (2006) proposed an improved approach for modeling of the optimal sizing parameters of Stand-Alone Photovoltaic Power (SAPVP) system especially in isolated sites where the meteorological data are not available. In addition to tra-

Figure 21. PVPS-system schematic (Mellit and Kalogirou (2006), used with permission)

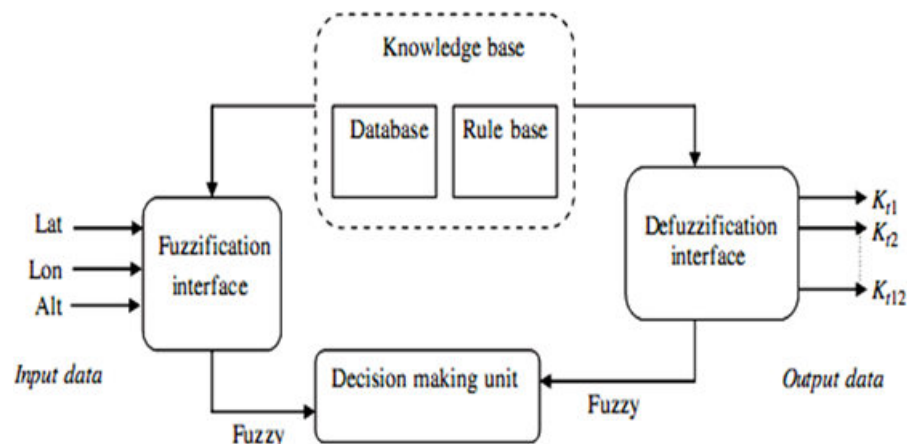


ditional models, several artificial intelligence based technique are studied and compared. These include feed-forward, radial basis function network, recurrent network, modular network, and the adaptive wavelet-network. The Proposed model consists to use an ANFIS scheme. The problem consists to predict the optimal parameters of SAPVP system in isolated sites, where the traditional models are not able to estimate these parameters in these sites. From these parameters we can determine the optimal configuration of the SAPVP system for a given load. A database of optimal sizing parameters has been developed by using numerical model for 200 locations in Algeria. The ANFIS model has been trained by using 200 known sizing parameters data, in this way the model was trained to accept and even handle a number of unusual cases. Known sizing parameters were subsequently used to investigate the accuracy of estimation, the unknown validation sizing parameters set produced very set accurate estimation with the correlation coefficient between the actual and the ANFIS model estimated data of 98.5% was obtained. Obtained results indicate that the proposed model can be successfully used for estimating the optimal sizing parameters of SAPVP system for any location in Algeria from only the geographical coordinates

of the considered site. The methodology can be generalized using different locations over the world, Senjyua *et al.* (2007) developed an optimal configuration of power generating systems in isolated islands with RE using a genetic algorithm (GA). This methodology can be used to determine the optimum number of solar array panels, wind turbine generators and battery configurations.

Hernadeza *et al.* (2007) presented a systematic algorithm to determine the optimal location and sizing of PV grid-connected systems (PVGCSs) in feeders that provides the best overall impact onto the feeder. The optimal solution is reached by multi-objective optimization approach. Both technical and economical objective functions are taken into account in the optimization procedure. The technical objective is related with the improvement of the distribution feeder voltage conditions. The economical objective is associated with the profitability both PV generation and potential loss reduction on the feeder. This procedure aims at finding the PV solution that yields the best compromise for the two considered objectives between various potential candidates of PVGCSs well known. The results obtained with the proposed methodology for feeders found in the literature demonstrate its applicability.

Figure 22. Fuzzy inference system (Adapted from Mellit *et al.*, 2008)



In a development of previous work, Mellit et al (2008) proposed an adaptive neuro-fuzzy inference system (ANFIS) model for estimating sequences of mean monthly clearness index () and total solar radiation data in isolated sites based on geographical coordinates. The magnitude of solar radiation is the most important parameter for sizing PV systems. The ANFIS model is trained by using a multi-layer perceptron (MLP) based on fuzzy logic (FL) rules. The inputs of the ANFIS in this model are the latitude, longitude, and altitude, while the outputs are the 12 values of the mean monthly clearness index. These data have been collected from 60 locations in Algeria. Figure 22 is showing the fuzzy inference used in this model. The results show that the performance of the proposed approach in the prediction of the mean monthly clearness index is better compared to the measured values. In addition, a comparison between the results obtained by the ANFIS model and ANN-based only models was conducted in order to show the advantage of the proposed method. The technique has been applied to isolated Algerian locations, but it can be generalized for any geographical position. It can also be used for estimating of other meteorological parameters such as temperature, humidity and wind speed

Benghanema and Mellit (2010) used a Radial Basis Function network for the modeling and predicting of the daily global solar radiation data from the meteorological data such as air temperature, sunshine duration, and relative humidity. These data were recorded in the period 1998-2002 at Al-Madinah (Saudi Arabia) by the National Renewable Energy Laboratory. Four RBF models have been developed, by the authors for the prediction of the daily global solar radiation. It was found that the RBF model which uses the sunshine duration and air temperature as input parameters, gives more accurate results. A comparative study between developed RBF, multi-layer perceptron and conventional regression models was also conducted in this paper. In addition, an application for estimating the sizing of

a stand-alone PV system at Al-Maidinah is presented to show the effectiveness of the developed RBF-model.

Interested readers in the applications of the AI techniques solar radiation, prediction and forecasting or in the AI applications in PV systems are strongly encouraged to read the following comprehensive review papers (Kallogirou, 2001 and 2003, Mellit, 2008, and Mellit and Kallogirou, 2009), as well as the Kallogirou, 2007 monograph.

CONCLUSION

A number of AI techniques have been reviewed in this chapter, which are suitable for solar energy applications. These include artificial neural networks, genetic algorithms, fuzzy logic and hybrid systems. AI techniques have been applied in a wide range of fields for modeling, prediction, and forecasting of solar radiation or solar resource estimates, simulation, modeling, optimization and seizing of solar energy systems. The advantages of AI-based simulation techniques are that they offer a powerful alternative approach to conventional physical modeling technique. These techniques do not require the knowledge of internal system parameters, involve less computational effort and offer a compact solution for multi-variable problems. The successful applications presented in this chapter are testimony of the potential of AI techniques in this field. Based on to the above applications, we can conclude the following:

- AI based models have been successfully developed to model solar radiation, clearness index and insolation. These have been used for estimating data in sites where measurement instruments are not available.
- AI techniques differ from the traditional ones in that no transformations of the data are required.
- AI techniques have been demonstrated and used in forecasting and prediction of the

solar radiation, clearness index and insolation, as well as for solving the problem of missing data.

- It should be noted that some models have been applied for specific location, but they can be easily generalized at different sites.

Based on the review presented here, AI techniques seem to offer alternative methods for modeling, forecasting and prediction of solar radiation in many regions of the world that lacks complete data. It should be noted that AI techniques have also been used for modeling and prediction of other meteorological variables, such as air temperature, wind speed, humidity, etc. that maybe used in the solar energy system design and operation. Generally, AI techniques have demonstrated the possibility for sizing PV-systems based on some available data successfully and with reasonable accuracy. Published literature on the sizing of PV-systems based on AI techniques indicates their popularity, particularly in isolated areas. This shows the potential of AI as a design tool in the optimal sizing of PV systems. The number of applications presented here is neither complete nor exhaustive, and interested readers are strongly encouraged to consult the rich references included in this chapter.

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KEY TERMS AND DEFINITIONS

Artificial Intelligence: Artificial intelligence is the mimicking of human thought and cognitive processes to solve complex problems automatically. AI uses techniques for writing computer code to represent and manipulate knowledge.

Artificial Neural Networks: Artificial Neural Networks are an approach to machine learning which developed out of attempts to model the processing that occurs within the neurons of the brain.

Fuzzy Logic: Fuzzy logic provides a way of taking our commonsense knowledge that most things are a matter of degree into account when a computer is automatically making a decision.

Genetic Algorithms: Search algorithms used in machine learning which involve iteratively generating new candidate solutions by combining two high scoring earlier (or parent) solutions in a search for a better solution.

Insolation: The solar power density incident on a surface of stated area and orientation (W/m^2).

Irradiance: The direct, diffuse, and reflected solar radiation that strikes a surface.

Photovoltaic System: A complete set of components for converting sunlight into electricity by the photovoltaic process, including the array and balance of system components.

Solar Constant: The average amount of solar radiation that reaches the earth's upper atmosphere on a surface perpendicular to the sun's rays; equal to $1353 \text{ W}/\text{m}^2$.

Solar Resource: The amount of solar insolation a site receives, usually measured in $\text{kWh}/\text{m}^2/\text{day}$, which is equivalent to the number of peak sun hours.

Chapter 16

Methods of Forecasting Solar Radiation

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ABSTRACT

Extreme demands on the methods used for forecasting solar radiation has been the driving force behind the efforts to find the best method available. An extensive study of different techniques available was conducted. Methods studied in this research can be classified as time series and neural network approach. Time series approaches considered are autoregressive (AR), moving average (MA), autoregressive moving average (ARMA), and autoregressive integrated moving average (ARIMA). In neural network approaches, multi-layer perceptron networks are used. The error back-propagation learning algorithm is utilized in the training process. Comparison of methods and performance of different methods are presented in the result and discussion section of this chapter. The solar radiation data used were a collection of past data acquired throughout the US continent for 10 years period. These data were used to forecast future solar radiation based on the past trend observed from the database using both time series and neural network approaches. Finally, this chapter makes general comparison among the methods used and outlines some advantages and disadvantages of using the neural network approach.

INTRODUCTION

Energy resources that are renewed on short term basis are designated as renewable energy resources. Almost all renewable energy resources considered for utilization at the present time are traced back to the sun. Wind energy, solar

radiation and heat, waterfalls, and biomass are different manifestations of solar energy and they have received most of the attention. They are fairly evenly distributed around the world and are plentiful (Ramakumar, Allison, and Hughes, 1974, pp. 107-115). However, these resources are dilute and conversion to usable forms requires quite an expensive tools.

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Solar radiation is the emission of photons from the sun. One of the ways these photons can be utilized is by means of the photoelectric effect: the primary effect of photons on solids. This effect was discovered by H. Hertz in 1887. The generation of a potential when the region in or near the built-in potential barrier of a semiconductor ionized by radiation is known as the photovoltaic effect. Photovoltaic effect was known long before its feasibility for direct energy conversion (Chaplin et al., 1954, pp. 676-677).

The concept of utilizing solar radiation for power generation using solid-state power plants has gained momentum (Moore, 1985, pp.6-19; Hoff and Shushnar, 1986; Calvo, 1995, pp. 916-921). The recent interest is primarily due to the decreasing cost of photovoltaic devices, coupled with their increasing conversion efficiencies. Solar heat is due to thermal agitation of matter initiated by the absorption of solar radiation. The sun has been used as a source of heat for a long time. For example, solar heat has been used, and still is, in many countries by farmers to dry their crops (Morhenne, et al., 1985, pp.1072-1076). Solar energy has been used for space heating and cooling since the fifth century B.C. Recently, the concept of utilizing the sun as a source of energy for heating purposes has also been gaining momentum (Kenna, 1984, pp.687-705).

Solar radiation is probably the most fundamental source of energy on earth. It activates not only the vital biological processes but also all meteorological systems. This is a significant variable that can affect the growth rates of crops, and is used in numerical models to estimate soil moisture, potential evapotranspiration, and photosynthesis (Tarpley, 197; pp.1172-1181). During recent years there has been an increasing trend in the study of solar radiation, due to the fact that the sun is practically the sole source of energy in the earth-atmosphere system. The requests for international solar radiation information have increased with the growing interest, especially in the use of renewable energy resources.

Solar Activity

Early earth-based measurements suggested that solar output was nearly constant; it varied within one percent imposed by absorption and scattering of sunlight in earth atmosphere (Gopal and Scuderi, 1995, pp.42-59). Satellite measurements made from the Solar Maximum Mission and Nimbus-7 showed constant changes of up to 0.1 percent for the most recent eleven-year sunspot cycle of the solar activity (Gopal and Scuderi, 1995, pp.42-59). The maximum of sunspots and solar activity is associated with a brighter sun.

Solar activities are rising rapidly. This causes an increase in the production of x-rays and extreme ultraviolet radiation (EUV) in the range of 100 and 1000 angstroms. The ultraviolet (UV) and EUV radiation varies and this matter has as a strong influence on the upper atmosphere of the earth. High solar activity also increases EUV radiation; it results in an increase in the temperature of the ionosphere. This temperature is three times greater than normal at 100 kilometers and above in the atmosphere. The increase in ultraviolet radiation in the upper atmosphere is also important because it affects stratospheric ozone levels (Gopal and Scuderi, 1995, pp.42-59). High solar activity can effect communication, computer systems, and can produce geomagnetic storms. These storms can induce electrical currents in power lines and oil pipelines at the earth's surface (Gopal and Scuderi, 1995, pp.42-59).

Nature of Solar Radiation

Solar energy has consistently been the most popular customer energy option in surveys conducted over past 20 years, prompting dozens of customer-focused utilities to exploit the solar energy to gain a competitive edge. Although such utilities are enticed in term of operating cost reduction, the chance to offer profitable and appealing products, and the chance to serve new customers their interest is not limited to what is cost effective and available

today (Bigger and Moore, 1995, pp.21-30). Utilities continue to invest resources in technologies that will afford them a competitive advantage in future. For example, utilities are cultivating markets to help achieve reduced photovoltaic costs quickly. In addition, other emerging technologies such as the solar dish engine and power tower (Bigger and Moore, 1995, pp.21-30) are actively pursued by the utilities.

The nature of the sun, which can produce solar radiation without any limitation, makes solar radiation a very reliable source of renewable energy. The sun also provides hydropower, wind power, and fossil fuel. Current technology allows radiation from the sun to provide non-polluting and cheap fuels, as well as electricity. It is unlikely that a single solar technology will predominate. Regional variation will naturally favor some approaches over others. Electricity can be generated by burning biomass, erecting wind turbines, building solar-powered heat engines, laying out photovoltaic cells or harnessing the energy in rivers with dams.

There is a new awareness of the advantages of utilizing renewable energy sources such as solar radiation, solar heat, wind, biomass, and falling water (Hughes, 1976). This is a consequence of realizing the limitations of conventional energy sources (oil, coal, and natural gas), the ever increasing demands being placed on the finite resources of the world (Hughes, 1976), and the adverse effects of utilizing conventional energy resources on the environment (Ashenayi, 1986). Also, conventional energy resources have some limitations. These include increasing prices and the adverse effects on the environment such as depletion of the ozone layer, air pollution, greenhouse effects, etc. There is one basic problem inherent to most of the renewable energy sources, that is their intermittent and highly variable nature (Hughes, 1976). The problem caused by the intermittency of these resources can be partially overcome by adding energy storage and reconversion facilities (Sorensen, 1976; Johnson, 1978, pp.554-562) and/

or by using the strengths of one source of energy to overcome the weakness of the other (Hughes, 1976). Either one of these approaches requires accurate forecast values of solar radiation to be effective.

In addition, many computer simulation models that are used to predict growth, development, and yield of agronomic and horticultural crops require daily weather-information as an input. One of these inputs is daily total solar radiation. Accurate and reliable knowledge of solar radiation is also needed for many other purposes such as design of buildings, air conditioning, snow melt calculations in hilly terrain, and solar power installations with tilted or moving collectors (Dincer, et. al., 1996, pp.183-198).

There are variable natures in this universe that can effect total solar radiation collected on the earth. These include cloud cover, wind speed, temperature, and precipitation. Some of these factors can increase solar radiation while others can reduce it. For example, when there is a large amount of cloud cover, solar radiation will be less because the sun light is blocked. Indeed, these variable natures can cause inconsistency in total solar radiation collected.

As is evident from the above discussion, due to the variable nature of solar radiation, it is difficult if not impossible, for it to be used as a reliable source without accurate forecasting.

INTRODUCTION TO FORECASTING

Prediction of future events and conditions is called forecast, and the act of making such prediction is called forecasting (Bowerman and O'Connell, 1991). The prediction work is very important these days in many kinds of organizations, especially in making future forecasts for the decision-making process of the organization. In the forecasting process, a forecaster normally relies on the past data to analyze the trend or the pattern of the event.

From the past data the forecaster will extrapolate or extend the pattern for the future forecast.

A forecasting technique sometimes does not give accurate results if the trend or pattern of the future event is not of the same trend as the past event. This situation usually happens when there are sudden changes in such event for example volcano eruption, hurricanes and earthquake.

Methods of Forecasting Solar Radiation

In general, forecasting methods can be divided into two basic types, which are qualitative and quantitative. The qualitative type requires no past data, while the quantitative type uses past data to forecast.

Quantitative type can be further divided into two groups: causal model and univariate model. Causal model involves the identification of other variables or input elements that can affect the forecasting process. The univariate model is used only when the prediction is based entirely on the past data without considering other variables. Forecasters only need to identify the pattern of the historical data set and assume the pattern will continue in the future.

Methods of Forecasting

Today, methods used to predict solar radiation must be able to forecast with a high degree of accuracy. Two methods considered in this research work are the time series and the neural network. Both methods are of quantitative type. The following section will describe briefly both methods and their approaches.

Time Series Method

Time series technique by Box and Jenkins (1976) is one of the traditional method that will be reviewed. The approaches based on the time series techniques are autoregressive (AR) model, moving-average

(MA) model, autoregressive moving-average (ARMA) model, and autoregressive integrated moving-average (ARIMA) model.

Time series have a chronological sequence of observations on a particular variable. As stated by Bowerman and O'Connell (Bowerman and O'Connell, 1991), the essential components of a time series should be identified in order to know the pattern of the event forecast. They essential components are the trend, cycle, seasonal variations and irregular fluctuations.

Trend is the nature of the movement that shows the time series over a period of time. Trend usually can tell the long-term pattern of the series. Cycle is the recurring up and down movements around the trend levels. The duration normally takes years that is measured from peak to peak. Seasonal variations are the pattern that is repeated annually based on its calendar year. Most of the time seasonal variations are affected by weather and custom factors. Irregular fluctuation is an occurrence of erratic movements that is not regularly happening in the time series pattern. It is neither recognizable nor regular. The most common examples of irregular fluctuations are when hurricanes, earthquakes, or other major disasters occur.

Neural Network Method

Neural network has been recognized as the most promising method to predict temporal series with chaotic or irregular behavior. It is also known that its prediction has a favorable performance compared to conventional statistical methods.

An approach using a feed-forward neural network may resolve some of the difficulties in forecasting. Feed-forward neural network is useful and practical. It is also proven as one of the best methods to approach nonlinear relations without knowing the actual underlying nonlinear function (Gopal and Scuderi, 1995, pp.42-59).

Other Methods

Besides time series and neural network methods, there are some other methods used to forecast solar radiations. In 1959, the first meteorological satellite was used to acquire data for the purpose of estimating solar radiation reaching the ground surface (Scalero and Tepedelenlioglu, 1992, pp.447-458). It was known as mapping solar radiation using satellite data.

Water vapor transmission is another method of prediction; this method measures the wavelength of the solar radiation absorbed by the water (PsiLoglou, Santamouris, and Asimakopoulos, 1994, pp.445-453). Water vapor absorbs light at specific bands of the solar spectrum and in order to estimate the solar radiation integral transmission function is used.

SELECTION OF FORECASTING METHODS

The selection of methods used is related to the cost of the operation. Most of the methods used promise an acceptable level of accuracy for forecasting data. These are only a small number of low cost methods that are within the acceptable percentage of accuracy.

There are some important factors that should be considered while selecting a forecasting method.

Bowerman and O'Connell (Bowerman and O'Connell, 1991) outlined some of the factors as follows:

- a. **The forecast form desired**
- b. **The time frame:** immediate, short-term, medium, or long-term
- c. **The pattern of data:** components of methods or series
- d. **The cost of forecasting:** cost of operations (storing data, programs used)
- e. **The desired accuracy:** the margin of acceptable error, that is the degree of accuracy a. required.
- f. **The data availability:** determine whether to use qualitative or quantitative method.
- g. **The ease of operation and understanding:** good understanding on the techniques of forecasting operation selected.

ERRORS IN FORECASTING

Accuracy plays a very important role in the field of forecasting. A very small percentage of error is allowed in order to obtain a high degree of accuracy. Normally, errors in forecasting exist when there are drastic events, for example earthquakes, hurricanes, flash flooding, or volcano eruptions. If the fluctuations in the data set are small, the result of the forecast will be more accurate.

Accuracy in forecasting also depends on the method that is used. Sometimes one method produces better results than the other. The selection of an appropriate method of forecasting is very important to avoid getting a low accuracy result.

The forecast error (E) is the difference between an actual value (A) and predicted value (P).

$$E_t = A_t - P_t \quad (1)$$

The squared error is

$$(E_t)^2 = (A_t - P_t)^2 \quad (2)$$

The average of the squared error is called the mean squared error (MSE), which is given as

$$MSE = \sum_{t=1}^n E_t^2 / n = \sum_{t=1}^n (A_t - P_t)^2 / n \quad (3)$$

where n is the total number of data points.

Percentage error of a forecast can be calculated as

$$\text{Percent error} = \frac{| \text{actual\_data} - \text{predicted\_data} |}{\text{actual\_data}} \times 100\% \quad (4)$$

Generally, most forecasters use 5% as an acceptable margin of error to have a high degree of accuracy.

CHRONOLOGY IN FORECASTING SOLAR RADIATION

The nature of methods used on the early forecasting stages are statistical and physical. Next the chronological developments of different methods are presented. In **1960's**. The first attempt by Fritz (Fritz, Rao, and Wanstein, 1964, pp.141-151) in 1964 that led to the possibility of predicting solar radiation from satellite data. In **1970's**. Vonder Haar (Vonder Haar, Raschke, Bandeen, and Paslernak, 1973, pp.175-184) used data from NIMBUSII to calculate the net radiation of the earth atmosphere. He used the principle of energy conservation; solar energy absorbed (G_a') in the earth's atmosphere system is the difference between the solar energy that enters into the system (G_0), and the quantity reflected by the system (G_r).

$$G_a' = G_0 - G_r \quad (5)$$

The error of estimation was 10% to 15% for daily total global radiation.

In 1980's. A number of methodologies were assembled for estimating solar radiation from satellite images. These methods seem feasible and promising for short and long term resource assessment of solar radiation.

A physical model was presented and details about the process of radiation were done separately for clear sky and cloudy sky (Islam, 1994, pp.103-113). Geostationary satellite data are used in the visible channel to calculate cloud and surface

albedos. Finally, an accuracy of about 9% error is obtained for daily and hourly total solar radiation.

There are also other approaches used to predict solar radiation, which also used geostationary satellite data. But, the results are not very impressive by looking at their standard errors. It was also *in the 1980's* that the neural network showed its potential in the field of forecasting, including forecasting solar radiation. Since then neural network has been an emerging tool for the purpose of forecasting. It has been shown that the neural network based methods give accurate and reliable results. There will be more discussion of neural networks method in the later chapters.

In 1990's. Researchers who used geostationary satellite data obtained a higher error of daily total global solar radiation even when they were using the improved model. Some of the error is due to the conflict between ground data and satellite data; there might be clouds during satellite scanning and no clouds at other times.

OTHER METHODS OF FORECASTING

The Half Sine Wave Model, Polynomial Model, and Ψ Model

Other methods used in the early works of forecasting solar radiation include the half sine wave model, the polynomial model and the Ψ model. The half sine wave model is not consistent in predicting the hourly solar radiation. Only 50% of the values predicted by this approach are within 10% of the actual values (Audi and Alsaad, 1991, pp.39-49). Only 10% of values predicted by the polynomial model are within 1% of the actual values. If the desired accuracy is within 10% then 51% of predicted values are acceptable.

Like the half sine wave model the polynomial model produces its best forecast for the noon hours, the most significant time in solar energy application. The Ψ model can correctly (error $\leq$

1%) predict 29.4% of the time. The same approach can correctly predict 67.7% of the time if we allow for errors up to 10%. The Ψ model curve passes through most of the data points except the early morning and late afternoon hours. By neglecting early morning and late afternoon hours of a given day the accuracy of this model increases significantly. Neglecting these hours 40.2% of the values predicted by this model will be within 1% of the actual value. In addition, 92.4% of the predicted values are within 10% of the actual values (Audi and Alsaad, 1991, pp.39-49). Table 1 summarizes the comparisons of these three models.

Prediction Using Data Missing from Long-Term Meteorological Records

Prediction using data missing from long-term meteorological records is developed to estimate daily total solar radiation using a 13 – year record of meteorological observations. A regression equation is developed to determine the daily solar radiation from maximum and minimum air temperature, pan evaporation, precipitation, and calculated extraterrestrial radiation (Hook and McClendon, 1992, pp.739-742).

Radiation predicted had the same variances and means as the observed data, and overall correlation of 78%. This method has a 53-year record with predicted solar radiation representing an intermediate step between computer generated radiation and fully measured data (Hook and McClendon, 1992, pp.739-742). The method presented should help to complete long-term weather records so that crop growth and water balance model can be applied to historical data.

TIME SERIES APPROACH OF FORECASTING

Time series approach of forecasting is widely used and is one of the most popular methods of forecasting. The most commonly used time series analysis methods are as follows:

- a. The autoregressive (AR)
- b. The moving-average (MA)
- c. The autoregressive moving- average (ARMA)
- d. The autoregressive integrated moving-average (ARIMA)
- e. The Box and Jenkins model.

The first two methods (AR and MA) were developed in the early phases of development of forecasting methods. Recently, the ARMA and ARIMA methods are being used more than AR and MA methods. The Box-Jenkins time series models are well know and suited for many applications in forecasting. The logical and organized procedures for model development using autocorrelation function make these approaches particularly attractive (Haggan and Behr, 1987). The following sections in this chapter describe the methods mentioned above in details.

THE MODELLING PROCESS

The Autoregressive Model

The most fundamental time series model are the autoregressive model (AR (p) and the moving-

Table 1. Comparison of the half sinewave model, polynomial model, and Ψ model

Model	error $\leq$ 1%	error $\leq$ 10%
Half sine wave	6%	50%
Polynomial	10%	51%
Ψ Model	29.4%	67.7%

average model (MA). In the AR model, current value of the process is expressed as a linear combination of p previous values of the process and a random shock.

$$Z_t = \varphi_1 Z_{t-1} + \dots + \varphi_p Z_{t-p} + a_t \quad (6)$$

By introducing

$$BZ_{t=Z_{t-1}}, \quad B^m Z_t = Z_{t-m}$$

and

$$\varphi(B) = 1 - \varphi_1 B - \varphi_2 B^2 - \dots - \varphi_p B^p$$

Equation (6) is simplified as

$$\varphi(B) Z_t = a_t \quad (7)$$

The Moving-Average Model, MA (q)

In the moving-average model, MA (q) the current value of the process is expressed as a linear combination of q previous random shocks.

$$Z_t = a_t - \theta_1 a_{t-1} + \dots + \theta_q a_{t-q} \quad (8)$$

In order to simplify Equation (8) we introduce

$$Z_t = \theta(B) a_t, \quad \theta(B) = 1 - \theta_1 B - \theta_2 B^2 - \dots - \theta_q B^q,$$

By combining Equation (6) and (8), we get a general autoregressive moving-average model (ARMA (p, q)), as expressed in Equation (9) and (10):

$$Z_t - \varphi_1 Z_{t-1} - \dots - \varphi_p Z_{t-p} = a_t - \theta_1 a_{t-1} - \dots - \theta_q a_{t-q} \quad (9)$$

$$\varphi(B) Z_t = \theta(B) a_t \quad (10)$$

The Autoregressive Moving-Average Model

The linear estimation in the time-series approach uses an autoregressive process to estimate the moving-average part. In order to obtain asymptotically efficient estimates, the autoregressive moving-average (ARMA) requires that order of the approximated autoregressive process approach infinity slowly.

Equation (9) and (10) illustrate the general ARMA model. The major practical problem of ARMA approach is selection of the order of the approach is selection of the order of the order of the approximated autoregressive process. Chiu (Chiu, 1991, pp.315-327), proposed an alternative estimation procedure based on the periodogram below,

$$I(\lambda) = (2\pi T)^{-1} dx(\lambda) dx(-\lambda) \quad (11)$$

where

$$dx(\lambda) = \sum_{t=0}^{T-1} x(t) \exp(-i\lambda t)$$

is the finite Fourier transform of the series $x(t)$, ($t=0, \dots, T-1$). Under some circumstances $I(\lambda_j)$, $\lambda_j = 2\pi j/T$, $j=1, \dots, N=((T-1)/2)$, are asymptotically independent exponential random variables with mean $f(\lambda_j, O_0)$.

The simple estimation procedure for an autoregressive moving-average process is expressed as in Equation (12):

$$\begin{aligned} x(t) + \alpha_{01} X(t-1) + \dots + \alpha_{0p} X(t-p) \\ = \varepsilon(t) + \beta_{01} \varepsilon(t-1) + \dots + \beta_{0q} X(t-q), \quad t = 0, \pm 1 \end{aligned} \quad (12)$$

where $\varepsilon(t)$ is a sequence of independent random variables with zero mean ($\mu=0$), variance (σ_0^2), and finite fourth order moment; $p, q \geq 0$ are the order of the process.

The likelihood function is quite intractable when $q \geq 1$, but the evaluation of this function is very complicated. A lot of work has been done to resolve this problem to find efficient estimates (Chiu, 1991, pp. 315-327).

ARMA estimates are obtained by application of autoregressive process and moving-average process alternately. It is known that

$$-\rho_k = \alpha_{01}\rho_{k-1} + \alpha_{02}\rho_{k-2} + \dots + \alpha_{0p}\rho_{k-p} \quad , \quad (k \geq q+1) \quad (13)$$

where ρ_u is the autocorrelation at lag u of series $x(t)$.

Chiu (Chiu, 1991, pp. 315-327) stated that the autoregressive moving-average process is close to a pure moving-average process. Hence, it is possible to obtain an initial estimate using pure moving-average before proceeding with the iteration.

Table 2 illustrates results of the experiment conducted in order to develop Akaike Criterion (Chiu, 1991, pp. 315-327) for ARMA (p, q). From Table 2, we can see that ARMA (1, 1) has the smallest Akaike Criterion. This means that ARMA (1, 1) gives the best estimate in this process.

Surveys show that only 5-10% of practicing forecasting use ARMA approach regularly. This is due to the difficulties and complications in determining the order of the process. Another

problem with using this approach is that the classical parametric hypothesis-testing paradigm underlying the Box-Jenkins approach is inappropriate (Beveridge and Oickle, 1994, pp.419-434). Thus, ARMA modeling is recommended only when series are free of trends and seasonality.

The Autoregressive Integrated Moving-Average (ARIMA) Model

ARIMA (p, d, q) model is a modified version of ARMA (p, q) model. It is called the integrated process of ARMA and the model forecasts are essentially extrapolations of previous history data. ARIMA models in forecasting solar radiation usually are inaccurate when there are sudden changes in the weather.

In order to model a stationary processes with finite variances, we use equation 3.4 and 3.5, and it is assumed that the roots of $\phi(B)$ and $\theta(B)$ lie outside the unit circle. Referring to Hagan and Behr (Haggan and Behr, 1987), one can model some types of nonstationary processes by differencing the original process, Z_p to obtain a stationary process, W_p where

$$W_t = \nabla^d Z_t \quad (14)$$

The result is the general ARIMA(p, d, q) model which is written as

$$\phi(B) \nabla^d Z_t = \theta(B) a_t \quad (15)$$

Table 2. Akaike criterion for ARMA (p, q)

q	p = 0	p = 1	p = 2	p = 3	p = 4
0	-2.05	-2.90	-2.97	-2.95	-2.95
1	-2.71	-2.98	-2.96	-2.95	-2.94
2	-2.91	-2.96	-2.95	-2.93	-2.92
3	-2.94	-2.96	-2.95	-2.93	-2.93
4	-2.92	-2.96	-2.94	-2.91	-2.92

where $\phi(B)$ is the generalized autoregressive operator. The generalized autoregressive operator is a polynomial of degree $p+q$ with exactly d zeros equal to the unity (Anderson, 1975). Therefore

$$\phi(B) = \phi_p(B)(1-B)^d = \phi_p(B)(\nabla)^d \quad (16)$$

where $\phi_p(B)$ is a stationary autoregressive operator of order p . The ARIMA (p, d, q) process for Z_t will reduce to an ARMA (p, q) process for W_t if we replace $\nabla^d Z_t$ by W_t . Then, the Z_t process can be obtained by integrating the stationary W_t process d times (Anderson, 1975). Therefore we called this process the autoregressive integrated moving-average (ARIMA) process.

ARIMA model uses $d \leq 2$, or $p+q \leq 2$ because it is not necessary to find the difference more than twice to produce a stationary series.

The highest order of ARIMA (p, d, q) process allowed in order to get the best result possible is $d \leq 2$, or $p+q \leq 2$. Box-Jenkins' observation showed that for the order of models not more than two looked generally reasonable for some data. In some cases it was found that higher order model was necessary. Therefore, the choice of order would depend on the objective of the modeling.

The ARIMA model relates an output Z_t to an input a_t in terms of the difference equation. The general form of ARIMA process of order ($0, d, q$) can be expressed in the difference equation form as follows:

$$\nabla^d Z_t = (1 - \theta_1 B - \theta_2 B^2 - \dots - \theta_q B^q) a_t = \theta(B) a_t \quad (17)$$

The model can be written in terms of z 's and a 's in the general form of

$$Z_t = dZ_{t-1} - 0.5d(d-1)Z_{t-2} + \dots + (-1)^{d+1}Z_{t-d} + a_1 - \theta_1 a_{t-1} - \dots - \theta_q a_{t-q} \quad (18)$$

The following examples illustrate the difference equations representing ARIMA processes of different order.

ARIMA process of order ($0, 1, 1$) can be represented by the following difference equation

$$\nabla Z_t = (1 - \theta B) a_t, \quad -1 < \theta < 1 \quad (19)$$

This model can be rewritten in term of z 's and a 's as

$$Z_t = Z_{t-1} + a_t - a_{t-1} \quad (20)$$

ARIMA process of order ($0, 2, 2$) has the difference equation form of

$$\nabla^2 Z_t = (1 - \theta_1 B - \theta_2 B^2) a_t \quad (21)$$

The process for the order of ($0, 2, 2$) is in the invertibility region where

$$-1 < \theta_1 < 1, \theta_1 + \theta_2 < 1, \theta_2 - \theta_1 < 1$$

The model also can be rewritten explicitly in terms of z 's and a 's as

$$Z_t = 2Z_{t-1} - Z_{t-2} + a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} \quad (22)$$

ARIMA model time series forecasting is particularly suited for short-term forecasting and forecasting highly seasonal variables. But, ARIMA model is the most versatile model of Box-Jenkins time series approach. One difficulty in dealing with this family of models was lack of an effective and objective criterion for selecting an optimal member (Moore, 1985, pp.6-19).

Autocorrelation Function Test

The Box-Jenkins forecasting models can be identified by testing the sample autocorrelation function (SAC) and the sample partial correlation function

(SPAC) (Bowerman and O'Connell, 1991). Techniques for preliminary identification of time series models rely on the analysis of autocorrelation function (AC) and the partial correlation function (PAC). These methods are very systematic and are extremely helpful in the determination of model order, in the preliminary estimation of model parameters, in diagnostic checking and model refinement (Haggan and Behr, 1987).

Sample of Autocorrelation Function

The sample autocorrelation function (SAC) has a working series of time series values $Y_1, Y_2, \dots, Y_n$. If the original time series values are neither stationary nor seasonal, a stationary time series may be obtained by using the first differential or the second differential transformation as in Equation 3.28 or Equation 3.29 respectively. In another case, if the time series is not stationary but seasonal, then the transformation will become more complicated. Refer to (Bowerman and O'Connell, 1991) for more detailed explanation.

Considering the working series mentioned above, the SAC at lag k , standard error, and t-statistic are calculated as follows.

The SAC at lag

$$k, r_k = \frac{\sum_{t=b}^{n-k} (Y_t - \bar{Y})(Y_{t+k} - \bar{Y})}{\sum_{t=b}^n (Y_t - \bar{Y})^2} \quad (23)$$

where

$$\bar{Y} = \frac{\sum_{t=b}^n Y_t}{n - b + 1}$$

The standard error,

$$S_{rk} = \frac{\sqrt{1 + 2 \sum_{j=1}^{k-1} r_j^2}}{\sqrt{n - b + 1}} \quad (24)$$

The t-statistic,

$$t_{rk} = \frac{r_k}{S_{rk}} \quad (25)$$

The value of r_k will always be in the range of -1 and 1. When r_k is close to 1, it has a strong possibility to move linearly with a positive slope, and when r_k is close to -1, it has strong possibility to move linearly with a negative slope (Bowerman and O'Connell, 1991).

The t-statistic is proposed as a criterion for the more complete evaluation of solar radiation estimation models (Stone, 1993, pp.289-291). In addition to providing a single integrated criterion for the evaluation and comparison of models, it also enables the model's predictions are statistically significant at a particular confidence level. The t-statistic is not meant to replace the widely used root mean square and mean bias errors, but to supplement them in aiding the model tester to quickly and reliably assess a model's performance (Stone, 1993, pp.289-291).

Sample of Partial Autocorrelation Function

The sample partial autocorrelation function (SPAC), as the SAC also has the SPAC lag k , standard error and t-statistic values. They are calculated as follows.

The SPAC lag

$$k, r_{kk} = r_1$$

if

$$k = 1$$

and

$$r_{kk} = \frac{r_k - \sum_{j=1}^{k-1} r_{k-1,j} r_{k-j}}{1 - \sum_{j=1}^{k-1} r_{k-1,j} r_j},$$

if

$$k = 2, 3, \dots \quad (26)$$

where

$$r_{kj} = r_{k-1,j} - r_{kk} r_{k-1,k-j}$$

for

$$j = 1, 2, \dots, k-1$$

There standard error,

$$S_{rkk} = \frac{1}{\sqrt{(n-b+1)}} \quad (27)$$

The t-statistic,

$$t_{rkk} = \frac{r_{kk}}{S_{rkk}} \quad (28)$$

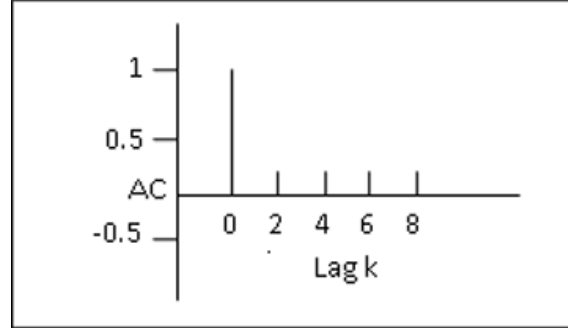
Development of Autocorrelation Function Model

The autocorrelation function describes an inherent correlation between observations of a time series which are separated in time by some lag k . For a white noise process, in which there is no correlation in time, the autocorrelation function is shown in Figure 1 (Haggan and Behr, 1987).

For an autoregressive process, the autocorrelation function is expressed as.

$$\rho_k = \phi_1 \rho_{k-1} + \dots + \phi_p \rho_{k-p} \quad (29)$$

Figure 1. Autocorrelation function of a white noise process



or

$$\phi(B)\rho_k = 0 \quad (30)$$

For example, from equation (6) we obtain an autocorrelation function of first order of autoregressive process as

$$Z_t = 0.5a_{t-1} + a_t \quad (31)$$

Figures 2 (a) and (b) show autocorrelation function and partial correlation function of a first order autoregressive process, respectively.

The partial autocorrelation function is also useful for determining the order of autoregressive process (Haggan and Behr, 1987). At lag k , r_{kk} is the solution for r_k if the order p is equal to k . From Figure 2(b), it is clear that the partial autocorrelation function is zero for all lags k greater than the true order of the process.

In the moving-average process, the autocorrelation function is identically zero for lags greater than the order process q (Haggan and Behr, 1987). From equation (8), we obtain the autocorrelation function of the moving-average process as

$$Z_t = a_t + 0.8a_{t-1} \quad (32)$$

Figure 2. (a) AR autocorrelation function; (b) AR partial autocorrelation function

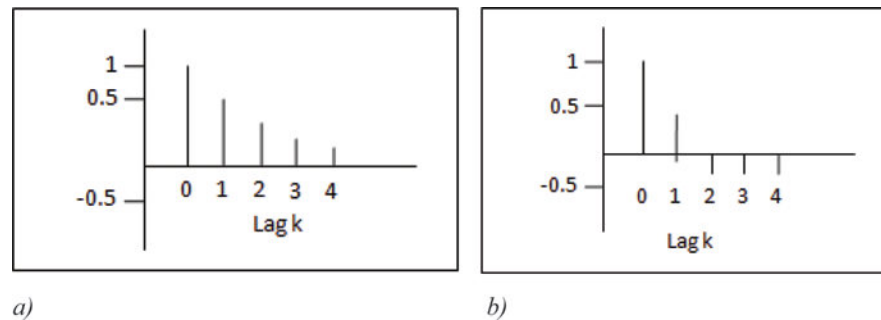


Figure 3. (a) Autocorrelation function (b) Partial Autocorrelation Function

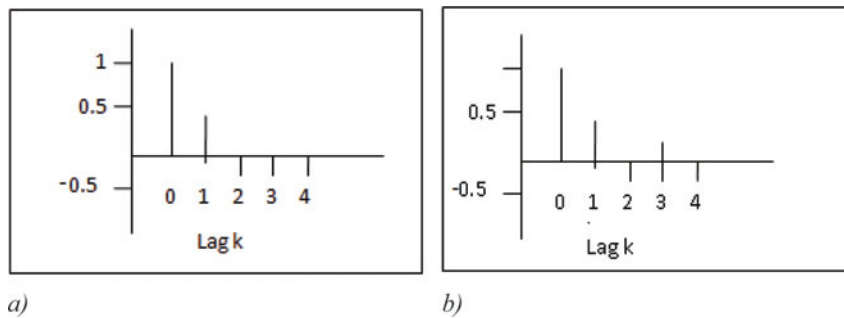


Figure 3.3 (a) and (b) show the autocorrelation function and the partial correlation function of a first order moving-average process respectively.

It is possible to use autocorrelation function and partial correlation function to determine the potential model structures. According to Hagan and Behr (Haggan and Behr, 1987), autocorrelation function and partial correlation function are very useful to determine the appropriate model adjustment when diagnostic checks indicate model inadequacy.

After the model structure is determined, the parameters are estimated using the method of maximum likelihood (Box and Jenkins, 1976). Then the residual, a_t , which is the one step ahead forecasting error calculated. Sequence of these residuals can be modeled using white noise. Otherwise, the autocorrelation function has to be investigated to identify modifications needed in order to improve the model.

THE BOX-JENKINS METHOD

The Box-Jenkins method consists of the several basic step as follows (Bowerman and O'Connell, 1991):

- Step 1:** Tentative identification: historical data are used to tentatively identify an appropriate Box-Jenkins model.
- Step 2:** Estimation: historical are used to estimate the parameters of the tentatively identified model.
- Step 3:** Diagnostic checking: various diagnostics are used to check the adequacy of the tentatively identified model, and if needed, suggest and improved model.
- Step 4:** Forecasting: once a final model is obtained, it is used to forecast future values of the time series.

Classical Box-Jenkins forecasting models describe stationary time series. A stationary time series has constant mean, μ and variance, σ^2 through time. If the series is not stationary, it can be transformed to a stationary series by taking the first difference of a nonstationary time series values.

For example, if we have series of $X_1, X_2, \dots, X_n$, then we take the first differences of each data as

$$Y_t = X_t - X_{t-1}, \quad t = 2, 3, 4, \dots, n \quad (33)$$

Sometimes we can also take the second difference of the time series, given as

$$Y_t = (X_t - X_{t-1}) - (X_{t-1} - X_{t-2})$$

therefore,

$$Y_t = X_t - 2X_{t-1} + X_{t-2} \quad (34)$$

for

$$t = 3, 4, 5, \dots, n$$

So, the series should have a constant mean and variance through time in order for it to be stationary.

INTRODUCTION TO NEURAL NETWORKS AND ITS APPLICATIONS

The idea of neural networks is based on the study of human brain. The human brain is made up of a special kind of cell called the neuron, which consists of dendrites, axon, nucleus, cell body, and synapse. Dendrites are neurons branches that connect to other neurons and provide the input to the neuron; axon is a long neural fiber that carries the neuron's output to other neuron's dendrites; synapse is a junction between the dendrite and

axon. Cell body converts the input provided by dendrites to an output that is then carried by the axon to the dendrites of other neurons (de Jongh and de Wet, 1993, pp.103-128).

Billions of neurons are densely interconnected and form a biological neural network. Although neural networks are inspired by the architecture of the human brain and aspire to imitate human intelligence, they do not exactly mimic the brain (de Jongh and de Wet, 1993, pp.103-128).

According to Lachtermacher and Fuller (Lachtermacher and Fuller, 1995, pp.381-393), neural networks are composed of two primitive elements: units (processing elements) and connections ('weights') between units. In essence, a set of inputs is applied to a unit that, based on their weighted values, produces an output. The connection of several unit's outputs to inputs of some other units make a neural network.

Neural networks have been proven to be a highly flexible function approximators and also universal to any data-generating process (Kohzadi, et. al., 1995, pp.463-474). These days they are considered as a powerful model for forecasting purposes even though the design of the network's architecture and learning rules are difficult to determine in order to obtain satisfactory results.

The speed of the information-processing in the neurons is about one million times slower than current computer gates, but the human brain is more efficient than the fastest computers in processing the complex tasks such as visual images and speech recognition due to the parallel processing capability (Kohzadi, et. al., 1995, pp.463-474).

Neural network is a promising area of artificial intelligence because it does not depend on human's ability to develop a model of the process that is to be modeled. Most of the successful applications of neural networks have been in the pattern recognition and classification domains (de Jongh and de Wet, 1993, pp.103-128). They did not become popular until 1985 when the error back-propagation learning method was developed. The error backpropagation can be used for forecasting

both linear and nonlinear time series. Traditional methods such as linear regression models could not completely capture information contained in a nonlinear series. Fortunately, neural networks that can capture this behavior are available (Kohzadi, et. al., 1995, pp.463-474).

DEVELOPMENT OF NEURAL NETWORK MODEL

In the development of neural network model, input variables play a very important role. The following inputs are considered as significant in predicting solar radiation: the daily observed values of the minimum and maximum air temperature and precipitation, daily calculated values for day length, and clear sky radiation. Day length and clear sky radiation are calculated as functions of latitude, day of year, solar angle, and solar constant. An optimum momentum, learning rate, and number of hidden nodes are determined for use in the development of the neural network model.

Then the neural network model is then tested against the test data set. The test data set consists of 20% of the recorded historical data. The remaining 80% of recorded historical data are used for the purpose of training. The results suggest that neural network can be used to estimate daily solar radiation when measurements of only daily maximum and minimum air temperature and precipitation are available.

Neural Network Model in Forecasting

Neural networks use a relation between sets of input data and observed output. Researchers have found out that neural networks have the capabilities to adapt changes in forecasting environment through the concept of self-learning. The network uses training cases to provide mappings to link input variables to output variables. In this research work, the output is the forecast of solar radiation.

In order to produce a forecast, first, the network will adjust the connection strength, called the weight, among the internal network nodes. This is done until the proper transformation linking past inputs and outputs from the training cases are learned (Peng, Hubele, and Karady, 1992, pp.250-257). Neural network has the potential to overcome the reliance on a functional form of the forecasting model (Peng, Hubele, and Karady, 1992, pp.250-257).

Neural network model used in the forecasting of solar radiation is based on a simulated multilayer feedforward network. Multilayer feedforward network consists of connected layers of units in feedforward designs. In other words neural network consists of a collection of simple inputs and processing neurons.

The neurons are arranged in interconnected layers known as input layer, hidden layer, and the output layer. These neurons are connected to each other by connection strength called weights. Weights connections are adjusted during the training of the network.

The number of neurons in the input layer is determine by the problem description. Let us consider the following case:

$$X_t = f(X_{t-1}, X_{t-2}, X_{t-3}, X_{t-4}, X_{t-5}) \quad (35)$$

where

X_t = the current value to be forecasted

$X_{t-1}, X_{t-2}, X_{t-3}, X_{t-4}, X_{t-5}$ = historical data used to forecast the current value.

From the problem above, five input nodes and one output node are needed. Figure 4 shows a model of the three layer network mentioned above. In this kind of network, each unit in the hidden layer receives an input which is a weighted sum of the network inputs.

At the processing stage, each neuron sums its weighted inputs, followed by nonlinear transformation. Finally the neuron sends its output to all neurons in the next layer, which is the output layer. Each unit in the hidden layer then performs a nonlinear transformation on its total input to produce the output, which is the forecast of solar radiation.

Equation 4.2 has a sigmoid activation or transfer function that introduces the nonlinearity into the technique. It squashes the input (which may have any value between plus and minus infinity) so that the output from each unit is scaled among 0 and 1. Figure 5 shows the sigmoid activation or transfer function.

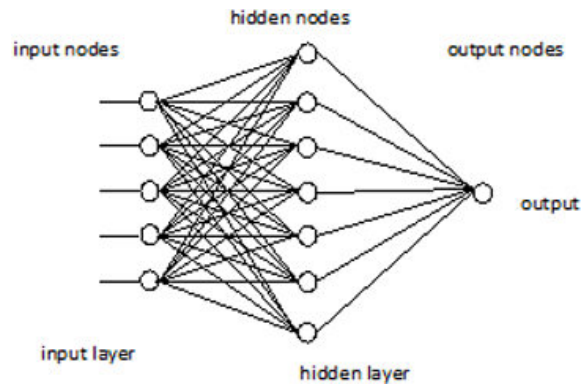
The sigmoid transfer function has the form:

$$\text{sig}(x) = f(x) = \frac{1}{1 + \exp(-x)} \quad (36)$$

where x = the sum of weighted inputs.

There is also another activation function that is also popular for forecasting purposes. This function is the tanh (see Figure 6) function. This

Figure 4. Three layer network



function will range the output between the range of -1 and 1.

The tanh transfer function has the form:

$$\tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \quad (37)$$

where x = the sum of weighted inputs.

The first step in developing a neural network based modeling for solar radiation is to normalize

Figure 5. Sigmoid transfer function

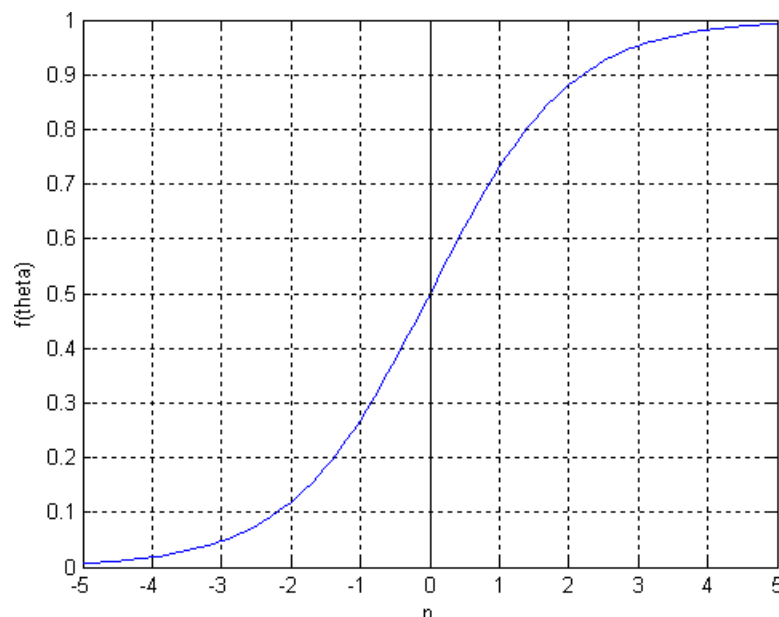
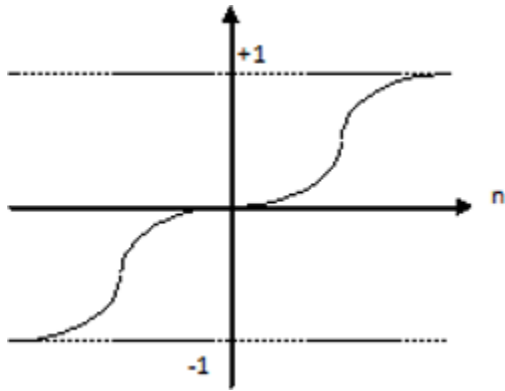


Figure 6. Tanh transfer function



the training set. During this step each recorded value is scaled linearly so that it lies between 0.1 and 0.9. This is needed in order to avoid saturating the activation function at its limit.

Training process is started by randomly setting the weights. Then a set of input-output pairs from the normalized past history of time series will be selected. An output is calculated by the network for a given input pattern. Then, the result is compared with the desired output by calculating the total squared error. Adjustments are made to the connection weights to minimize cost function across all output units by using the error back-propagation learning algorithm.

One study shows that 25 hidden units were found to be adequate for forecasting solar radiation (Macpherson, 1993, pp.447-450). Performance remains the same with minor fluctuations when the number of hidden units is increased beyond twenty-five (Gopal and Scuderi, 1995, pp.42-59). Average error over the training period was less than 5% and the worst was about 10%, after 2500 iterations (Macpherson, 1993, pp.447-450). In this study, a three-layer network was used. In addition, the study showed that this kind of network is more stable when iterating from maximum to minimum.

Feedforward Neural Networks

Artificial neural network is intended to interact with objects of the real world similar to biological systems. A feedforward network is one where connections only exist between any single unit and every unit in the previous layer. However, there is no connection between units in the same layer. This type of network has been known to be able to approximate any given continuous function to arbitrary accuracy by giving large enough number of units in each layer (Macpherson, Conway, and Brown, 1995, pp.21753-21744).

Multilayer perceptron is an example of feedforward neural network. It has been used in a number of applications such as speech and image recognition (Scalero and Tepedelenlioglu, 1992, pp.447-458). They have hidden layers that can overcome many limitations of single layer perceptrons. These feedforward networks are trained ahead of time by using known input and output data (Scalero and Tepedelenlioglu, 1992, pp.447-458).

The feedforward backpropagation neural network is one of the most popular neural network topologies (Setiono and Hui, 1995, pp.273-277). There are advantages to using these topologies such as ease of understanding and implementation. Before the training starts, the number of hidden units has to be determined; the minimum number required by neural network to solve a particular problem is usually determined by trial and error (Setiono and Hui, 1995, pp.273-277).

Even though this feedforward backpropagation method is considered as an easy method, there are still some problems in deciding the number of hidden units. If too many hidden units are used, the time for one training cycle increases and the resulting network may not generalized well. If too few hidden units are used, it may not be possible to train the network to solve the problem (Setiono and Hui, 1995, pp.273-277).

These difficulties have been studied and new algorithms have been developed. These new training algorithms will automatically add hidden units as they are needed or remove those that are redundant (Setiono and Hui, 1995, pp.273-277).

Collection of Solar Radiation Data

Solar radiation data are usually collected on an hourly basis by surface meteorological observation stations. The stations are located in the continental US at different altitudes and elevations. Due to different time zones across the country, data recorded at different stations need to be synchronized. All digitized data are synchronized in the International Systems of Units (SI).

Neural Networks Learning

Learning in neural networks is carried out by adjusting the weights such that the final set of weights can map inputs to the output(s) (Kohzadi, et. al., 1995, pp.463-474). Two ways that are most commonly used in network learning are supervised and unsupervised learning. In supervised learning, the network is presented with both inputs and the desired output. This way the network can make a comparison between the results and the desired output, and also minimize the error.

In unsupervised learning, the network is not presented with the desired output. The network itself will try to classify the inputs according to the features presented in the inputs. The supervised learning is the most commonly used learning algorithm in forecasting.

Training the Networks

The purpose of training the network is to find the connection weights, then from the output we can determine whether this neural network method is capable of doing forecasting works. In order to determine the correctness of the forecast, the output is compared to the past data that we already

have. For example, if we want to find the forecast on Monday in 1971, take the Monday data from the years before 1971 as input. This way we can determine the accuracy of the forecast by comparing the network output and the actual data.

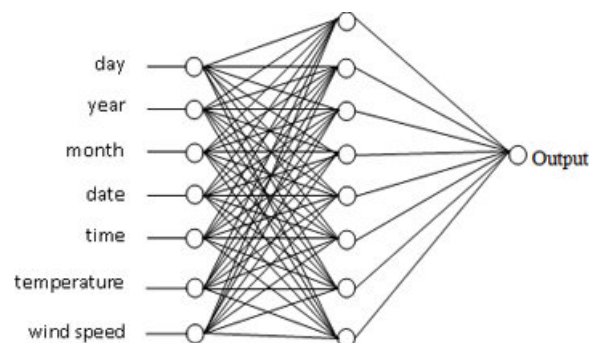
In order to train a network, input vectors and the corresponding output vectors are presented to the network. This is done until the vectors can approximate a function, associate input vectors with specific output vectors, or classify input vectors in an appropriate way as defined by the user. Then error vectors and the sum of the squared errors are calculated. If for all training vectors the sum of squared errors is less than a prescribed goal error, then the training will stop. On the other hand, the delta vectors are calculated for the output and hidden layers and back-propagated through the network. Finally the weights are updated using the backpropagation learning rule and the process repeats until the sum of the squared errors is less than the goal error.

The input data are fed to the network input (call feed-forward) and then we used the backpropagation learning rule to train the network. Figure 7 shows how the inputs are fed into the network.

To summarize the training process, it can be classified into four phases. They are:

1. **Presentation Phase:** Present an input training vector and calculate each successive

Figure 7. Feed-forward network with input elements



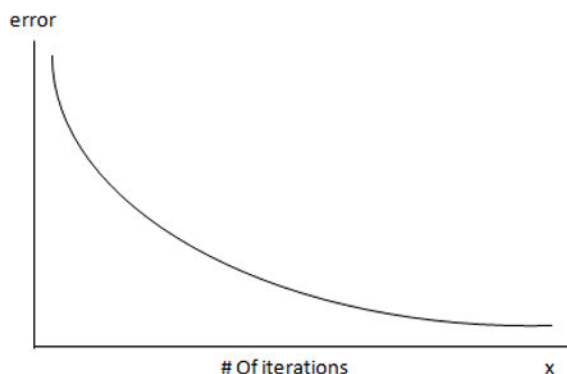
- layer's output until the last layer's output is found.
2. **Check Phase:** Calculate the network error vector and the sum squared error for the input vector. It will stop if the sum of squared errors for all training vectors is less than the goal error or if our specified maximum number of epochs has been reached. Otherwise it will continue.
 3. **Backpropagation Phase:** Calculate the delta vector for the output layer using the target vector. Then backpropagate the delta vectors to preceding layers.
 4. **Learning Phase:** calculate each layer's new weight matrix and new bias vector. Then return to phase 1.

A network can also be over-trained. Over-training occurs when the network is presents with the training decreases as the network learns. Figure 8 illustrates the error versus number of iterations or cycles in the training. Point x on Figure 8 shows where the training is to stop so that the network will not be over-trained. Over-training can cause the algorithm to memorize the data from previous process and it will not produce accurate results.

Backpropagation

Backpropagation was created by generalizing the Widrow-Hoff learning rule to multiple-layer

Figure 8. Error versus # of iterations



networks and nonlinear differentiable transfer function (Demuth and Beale, 1993). This technique was selected to learn the algorithm because this algorithm can learn from examples and accept non-binary values as their inputs. Since the algorithm is based on gradient-descent, the mean-squared-error between desired output and actual output will be minimized.

The back propagation learning rules are capable of making adjustment to the weights and biases of the networks and also minimize the sum of squared errors of the networks. Derivatives of error are calculated for the network's output layer. Then it is backpropagated through the network until the derivatives of error that is also known as the delta vectors, are available for each hidden layer. The convergence rate is largely dependent on the number of hidden units, initial state of the system, and the learning rate (Gopal and Scuderi, 1995, pp.42-59).

Other Methods Using Neural Network

Neuroshell™ (Ward System Group, Frederic, MD) is a software that contains a user-friendly back-propagation implementation (Elizondo, Hoogenboom, and McClendon, 1994, pp.115-132). Neuroshell™ is a menu-driven program for developing neural network models. It includes several utilities for data manipulation, model development, graphical options, and a runtime option to generate source code (Elizondo, Hoogenboom, and McClendon, 1994, pp.115-132).

One of the most important feature of neuroshell™ is that it can prevent-learning. Over-learning process will reduce accuracy of forecasted results.

In Neuroshell™, maximum acceptable error is set by the user (Elizondo, Hoogenboom, and McClendon, 1994, pp.115-132). This is the error between the actual and forecast output for each pattern presented to the network. If the error is greater than the acceptable value, the weights are

adjusted by the back-propagation algorithm until the error is at least below the specification.

Neural network is considered as the most reliable method to produce an accurate result. Overall it still has a tendency to over predict solar radiation on the low values and under predict solar radiation at the high values of the data set. To test suitability of neural networks for forecasting solar radiation, a network was trained. The values predicted by the neural network have day-to-day variations that are similar to the observed solar radiation.

Accuracy of our network forecasting solar radiation can be improved by adding other field-measured parameters such as percentage of cloud cover, solar brightness or pan evaporation.

RESULTS AND COMPARISONS

In this section, results of the comparison of the different methods used by the forecast practitioners are presented. Most of the comparisons will be between the Box and Jenkins methods and neural network method. These methods are compared on their accuracy, cost of the forecasting works, efficiency of the methods used, and reliability of the model.

General Comparisons

The accuracy of the methods varies from one method to another. Forecast practitioners who used neural network methods usually set their margin of error within 5% of the actual data (Beveridge and Oickle, 1994, pp.419-434). They normally did not tolerate percentage error greater than 5% because it will cause inaccuracy in their predictions. The cost of using this forecasting method is within the acceptable range, even though time taken to train the networks sometimes can be as long as days or weeks.

Box and Jenkins presented a reliable forecasting method at the beginning of the forecasting era. But, as time goes by and new technologies are

introduced, this method is rarely used by forecast practitioners. This is due to the complication of transforming data from one series to another. The time series method used by Box and Jenkins has its own approach to obtaining an accurate result. However, it is not as accurate as the neural network method (Beveridge and Oickle, 1994, pp.419-434).

Time series can determine the trend seasonal or nonseasonal, cycle, and variation of data predicted. Transformation of the series from nonstationary to stationary also helps the series to behave more accurately toward the actual forecast. This could reduce the fluctuations on the highs and lows of forecast data.

Present study used small time series (40 to 60 elements) and achieved a better performance than the corresponding ARIMA model especially for non-stationary series in a very short training process. Table 3 shows the comparison between neural network method and ARIMA method (Kohzadi, et. al., 1995, pp.463-474).

Referring to Table 3, it shows that the mean of the mean absolute percentage error (MAPE) of the neural network model is about 18% less than the ARIMA model. The mean of mean square error of the neural network model is about 40% less than the ARIMA model. This shows that the neural network model can yield better accuracy than the ARIMA model.

Comparison of Box-Jenkins Method to Conventional Methods

The Box-Jenkins approach in forecasting is well known where this method is using the time series application in its forecasting model. The Box-Jenkins method was also used to determine the optimal order of p and q in and autoregressive and moving-average components, respectively, for a stationary ARMA(p, q) series (Beveridge and Oickle, 1994, pp.419-434).

The Box-Jenkins method is subjective in the sense that analysts can see and verify different

Table 3. Comparison of the mean absolute percentage error (MAPE) and mean squared error (MSE) between neural network and ARIMA model

Sample	NEURAL NETWORK			ARIMA	
	MAPE	MSE		MAPE	MSE
1	1.27	25.60		1.31	35.10
2	1.06	16.42		1.40	24.20
3	1.93	44.20		2.68	52.44
4	2.70	39.53		2.42	28.99
5	2.25	25.78		3.67	23.07
6	2.47	93.56		1.96	40.23
7	1.18	12.53		1.75	37.06
8	1.27	13.65		1.87	37.04
9	1.56	21.57		1.62	24.88
10	1.55	21.03		1.69	22.84
Mean	1.72	31.56		2.03	53.24

models while using the same set of data, significance levels, and computational techniques (Beveridge and Oickle, 1994, pp.419-434). But, the Box-Jenkins method is not widely used for the autoregressive and moving-average processes. Surveys indicate that only 5% - 10% of practicing forecasters use Box-Jenkins approach for the autoregressive and moving-average processes regularly.

The Box-Jenkins method is also time consuming. The cost of producing the accurate forecast is also very high. Even though the cost of the computational component continues to decrease, the direct and opportunity costs for the analysts do not. This is not a good sign for a forecasting work.

S. Beveridge and C. Oickle (Beveridge and Oickle, 1994, pp.419-434) noted that a full Box-Jenkins analysis of each series may not be feasible even without cost constraints when forecasting many series within a limited period. Forecast practitioners think that cost and ease of use is as important as getting an accurate result when selecting the method of forecasting.

Model-building process requires a significant amount of planning and consideration before selecting the forecasting procedure. ARMA mod-

eling does not get a high mark by Box-Jenkins method; the classical parametric hypothesis-testing paradigm is not appropriate either. Neither routine is adequate for producing cost effective and accurate result; even though ARMA model reduces the prediction error by 10% of the average mean-square-error over the old regression techniques.

Advantages and Disadvantages using Neural Network

The main advantage of the neural network is its ability to accurately predict solar radiation. This is evident from results presented in Table 2, where it was compared to ARIMA model. Neural network approach also has a greater flexibility in model development than the multi-linear regression approach. In addition, it is easy to apply. Also, neural network can produce reasonable results when some data are missing or are in error.

The main disadvantage of the neural network approach is the inability to explicitly present the predictive equation. However, this does not prevent neural network model from producing successful results in other applications.

Training neural network could also be time-consuming. This problem is due to the large number of parameters being calculated. In addition, it may require a large number of observations in order to avoid over fitting. Although, the accuracy of using neural network method is high, it do not always converge to an acceptable solution.

Overall, neural networks appear to be promising for forecasting short-term data such daily, weekly, or monthly data. This class of data is more likely to be nonlinear and contain enough observations to avoid the over-fitting problem.

CONCLUSION

The neural network forecasting model has demonstrated that it is a better model than ARIMA for forecasting tasks. The results are consistent with the idea that neural network is a powerful method that possesses flexible functional form properties. Therefore, it is a useful model for forecasting purposes, especially when the underlying data-generating process is not known.

The design and architecture of neural network have lack of detailed explanation and comprehensive theory (Kohzadi, et. al., 1995, pp.463-474). There is no fixed architecture that we can use for certain problems. The final result of the network involves some trial and error before it converges to a satisfactory result. Researchers should make some improvement on these difficulties.

The backpropagation algorithm is successfully used in many cases of training the neural networks. Many iterations are required to train small networks for even a very simple problem (Scalero and Tepedelenlioglu, 1992, pp.447-458). Training large network structures and data sets may take days or weeks using the backpropagation algorithm. It would be beneficial if there were a training algorithm that could reduce this long training time as well as the cost of the process.

Some complex and unstable problems can be trained quickly when a low learning rate and momentum are used. Introducing a new alternative algorithm that can be considered faster than be backpropagation algorithm is a good step towards improving the existing algorithm.

A work done by Scalero and Tepedelenlioglu (Chiu, 1991, pp. 315-327), has an added advantage of being less affected by poor initial weights and setup parameters. This new algorithm uses a modified form of the backpropagation algorithm in order to minimize the mean-squared error between the desired output and the actual output with respect to the summation outputs (Scalero and Tepedelenlioglu, 1992, pp.447-458). This is different from the backpropagation algorithm where the mean-squared error is minimized with respect to the weights.

The present methodologies using the existing satellite data are sufficient for producing a solar radiation prediction system. The data are very useful for engineering applications involving the development of energy technologies and assessments of environmental, climatological, and agricultural parameters for the sustainable development of the economically lagging countries (Scalero and Tepedelenlioglu, 1992, pp.447-458).

As computers become cheaper, more powerful, and better programs are developed, generally the task of forecasting will be accomplished more efficiently. The critical issue is the difficulty in choosing the right program for the successful implementation of forecasting methods. It should be viewed as the best way to identify and extrapolate patterns or relationships. The forecasting errors should always be investigated so that in the future the cause of those errors can be easily identified. Forecast practitioner should also identify the nature and size of common errors that occur in their work so that they can avoid or at least minimize same mistake in the future.

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KEY TERMS AND DEFINITION

AR Model: Current value of the process is expressed as a linear combination of p previous values of the process and a random shock.

ARIMA Model: Relates an output Z_t to an input a_t in terms of the different equation.

ARMA Model: The linear estimation in the time-series approach uses an autoregressive process to estimate the moving-average part.

Forecasting: Prediction of future events and conditions is called forecast, and the act of making such prediction.

Neural Network: A method to predict temporal series with chaotic or irregular behavior.

Renewable Energy: Energy resources that are renewed on short term basis.

Solar Radiation: The emission of photon from the sun.

Chapter 17

Greenhouse Solar Thermal Application

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ABSTRACT

This chapter includes brief description of different solar thermal applications of greenhouse structure based on the different research work done in this area. It provides the basic knowledge of the use of solar energy to increase the production of different agricultural products using greenhouse system, e.g., crop production and drying of agricultural products. The chapter includes the introduction of greenhouse system, the definition, the concept, and the importance of greenhouse technology. The uses of various solar thermal applications in different greenhouse systems such as flat plate collector in greenhouse fish pond system and application of photovoltaic system in greenhouse drying are covered in this chapter.

INTRODUCTION

Greenhouse structures are used to provide the ideal condition required for the growth of agricultural crops throughout the year. The objective of this chapter is to provide a platform to disseminate the fundamental knowledge of greenhouse structure with various solar thermal applications, which includes:

- Fundamentals of greenhouse technology
- Different design of greenhouse structures with different solar thermal applications
- Basic working principles and energy balance
- Thermal analysis

The aim of this chapter is to provide an insight in the subject. We have drawn materials from different journals and books related to the subject.

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According to EncyclopediaC2000 (Anon, 2000) the greenhouse effect for environment is defined as: *“Greenhouse Effect, term for the role the atmosphere plays in insulating and warming the earth’s surface. The atmosphere is largely transparent to incoming solar radiation. When this radiation strikes the earth’s surface, some of it is absorbed, thereby warming earth’s surface. The surface of the earth emits some of this energy back out in the form of infrared radiation. As this infrared radiation travels through the atmosphere, much of it is absorbed by atmospheric gases such as carbon-dioxide, methane, nitrous oxide and water vapor. These gases then re-emit infrared radiation, some of which strikes and is absorbed by earth. The absorption of infrared energy by atmosphere and earth, called the greenhouse effect, maintains a temperature range on earth that is hospitable to life. Without the greenhouse effect, the earth would be frozen planet with an average temperature of about -18°C (about 0°F)”*. Similarly this phenomenon accomplishes at the micro level, for a house having the transparent walls and roofs (glass, Perspex or polyethylene film), when the solar (short wave length) radiation passes through the transparent walls and roofs it is absorbed by some object inside and then warming up the object. The warm object emits heat in the form infrared (long wave length) radiation, which cannot be re-radiated back outside due to glass cover, resulting in increase in temperature. This house is thus called greenhouse. Today greenhouse is mainly used for the maximized the production of crops mainly during the off season, because inside greenhouse the favorable condition for the optimum growth of the agricultural crops is possible. Greenhouse is used to maintain the favorable condition required for increase the productivity of the crop. The environment such as light, air composition, temperature and nature of the root media has significant effect in the production of agricultural crop (Tiwari, 2003).

CLASSIFICATION OF GREENHOUSE SYSTEMS

On the basis of working principal applications, greenhouse may be broadly classified in the three categories:

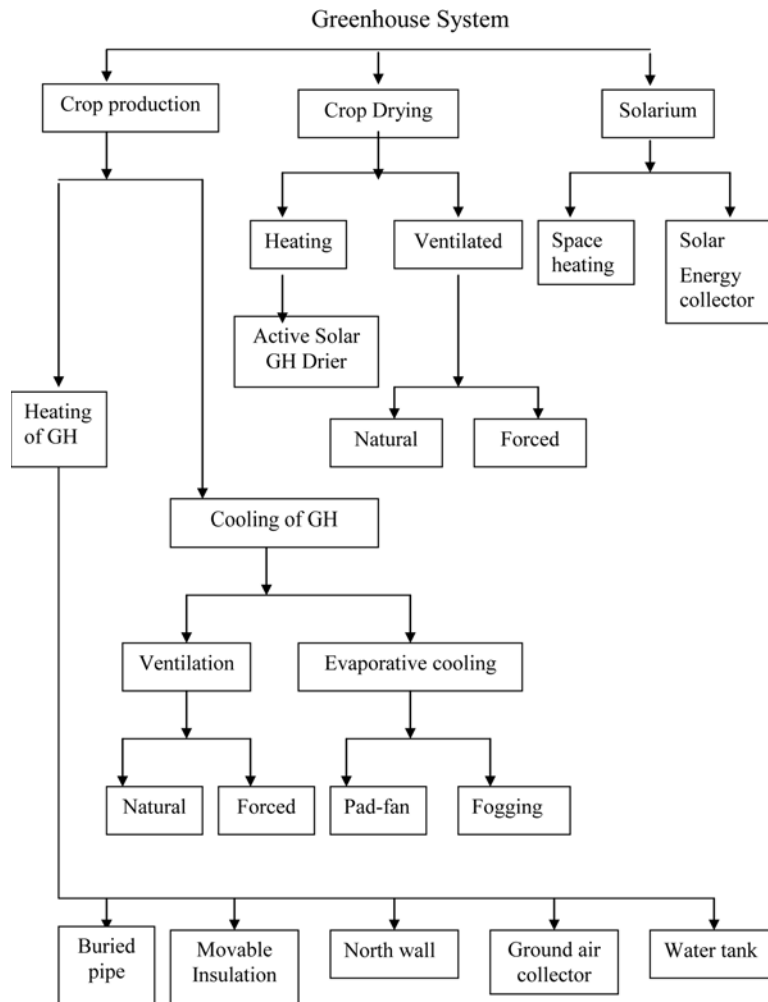
1. Greenhouse for crop cultivation,
2. Greenhouse for crop drying
3. Greenhouse as the solar energy collector

The detailed classification on this basis is shown in Figure 1.

BACKGROUND

Greenhouse pond system (GPS) can provide a good alternative for maintaining water temperature in aquaculture facilities (Zhu et.al, 1998). One of the most important factors influencing fish growth is the water temperature (Brett and Groves, 1979; Corey et al., 1983). Many of the most popular fish species have optimum growth temperature between 25° and 32°C , thus making their culture applicable only during the warmer months (Stickney, 1979). Growth rate increases with increasing water temperature, but when the temperature is above the optimum, it has a negative instead of a stimulatory influence (Jobling, 1993). In low temperature regions, the metabolic activity of fish is greatly reduced, which affects the growth-rate of the fish (Halver, 1972). A few reports are available on greenhouse or plastic shelter pond that could achieve a $2.8 - 4.4^{\circ}\text{C}$ increase in water temperature for each month of the year when compared with an open-air pond (Klemetson and Rogers, 1985). A Rise of 9°C in water temperature was achieved (Brooks and Kimball, 1987) in January in Phoenix, USA in a solar heated aquaculture pond. Again rise of $4.13 - 6.92^{\circ}\text{C}$ water temperature was achieved for greenhouse pond connected with two numbers of collectors and in case of without collector it was

Figure 1. Classification of greenhouse system (Source: Tiwari 2003)



3.12-5.64°C (Das and Tiwari, 2006). A number of studies have demonstrated the enhancement of fish growth-rate inside the greenhouse by using common carp species (Naegel, 1977; Wisely et al., 1981; Wood and Ghannudi, 1985; Bandyopadhyay et al., 2000; Kumar et al., 2001; Mohapatra et al., 2002; Frei and Becker, 2005).

Greenhouse is another option for reducing heat loss and simultaneously enhancing water temperature. The advantages of greenhouse are: (a) reduction of air velocity, (b) reduction of temperature difference between the pond and surrounding air, and (c) reduction of vapor pressure difference between the pond water and air (increased relative

humidity). These effects reduce the losses associated with evaporation, convection and radiation. Heat loss dependent upon the local climatic factors such as wind velocity, mixing of water within the pond, temperature gradient between the pond and ambient air, and relative humidity (Tiwari, 2003). Thermal modeling of greenhouses for agriculture, horticulture and floriculture purposes has been performed by numerous investigators (Khatry et al., 1978; Chandra and Albright, 1980; Tiwari and Dhiman, 1986; Santamouries et al., 1994; Tiwari, 2003). Although there are many studies available on fish culture inside greenhouse, which depends largely on the management practices and

the species used (Kumar et al., 2000; Frei and Becker, 2005). But, these Passive greenhouse or direct gain system is not sufficient for heating the pond water, where higher water temperature is required. A more effective and reliable method to increase the water temperature is by introducing a flat plate collector as indirect heating. This system is similar to the active solar still, but solar still water depth is usually maintained below 0.15 m. Simulation of integrated collector storage solar heater system was performed (Smyth et al., 1998). The performance of a multiple-effect vertical solar still with a flat plate collector was analyzed (Kiatsiriroat et al., 1993) and also the performance with active solar still was analyzed (Tripathi and Tiwari, 2005).

Drying is practice to preserve the food for longer duration. Some traditional techniques for improving preservation and storage are salting/brining, open sun drying and smoking open sun drying is still the most common method used for preserving food products in tropical and subtropical countries. In comparison to open sun drying the use of greenhouse dryer lead to reduction of the drying time up to 50% and to a significant improvement to the product quality in terms of color, texture and test (Esper and Muhlbauer, 1998). High temperature drying shows significant advantages on rice quality in terms of energy saving and quality deterioration, especially fungal deterioration (Wiset et al., 2001). Furthermore, the contamination by insects, microorganisms and bacterial fungi can be prevented. The storage losses can be reduced to a minimum while the shelf life of the products can be increased significantly. Properly designed greenhouse dryer allow a great degree of control over the drying process than the cabinet dryer and are more appropriate for large-scale drying (Anon, 2000). Researchers have recommended greenhouse as a dryer for drying different agricultural products (Shaw, 1981; Sadydov and Khairiddinov, 1982; Muthuveerappan et al., 1985; Jain and Tiwari, 2004; Kumar and Tiwari, 2006; Das and Tiwari, 2008; Barnwal and Tiwari, 2008).

A modular solar dryer was developed (Farkas et al., 1999) in which PV panel (maximum power 2x20W) to drive an electrical fan for artificial air circulation was installed in the front side of the dryer with changeable elevation angle suitable to the different angle of sunshine in the different period of the year. The convective mass transfer of grape was evaluated when dried in a hybrid PV/T integrated greenhouse dryer under forced mode (Barnwal and Tiwari, 2008).

GREENHOUSE FISH POND SYSTEM (GPS)

Water temperature control is generally more important for aquatic species than land animals. When the water temperature is below the optimum range (25-32°C), the fish lose their ability to feed because the basic body metabolism is affected. Fish growth for a given variety is controlled by its environment. Therefore, the environment should be suitably controlled to tap the full potential of given species and size. Greenhouse is the frame of inflated structure covered with transparent material over the pond in which fish are grown under partial or fully controlled environment conditions. These are large enough to allow a person to walk within its structure to carryout cultural and other operational activities. Sometimes, it is referred as surface covered cultivation. There have been innumerable studies qualifying the effect of environmental parameters individually as well as collectively on fish production. There for creating a favorable environment means a significantly higher growth of fish and its yield. The conventional aqua cultural practices can only control management practices. It does not ensure control over water temperature during culture period under open condition.

Water temperature is an important factor on yield, as well as the length of growing season and the quality of fish production. A few types of passive aquaculture greenhouse have been reported

and used. In all the cases, the basic strategy is to reduce heat loss, increase water temperature and at the same time, increase fish production.

Greenhouse design is strongly influenced by the climate and the latitude of the location and its structure is supposed to withstand loads because of its own weight, wind and snow, hanging baskets and should allow maximum light transmission (Santamouris et al., 1994; Tiwari and Dhiman, 1986; Elsner et al., 2000; Tiwari, 2003). The choice of a greenhouse type by the fish farmers depends on locally available material and economic conditions. In many cases, local tradition and existing greenhouses play an important role in the decision-making. In particular, a local economic consideration is influenced the popularity of certain types greenhouse.

Experimental Greenhouse Fish Pond System

The experiment was carried out in a Quonset shape greenhouse (popularly known as IARI model) at Solar Energy Park, IIT Delhi (Latitude-28°35' N, Longitude-77 ° 12' E and an altitude of 216 m above mean sea level). The dimension of the Quonset shape greenhouse (popularly known as IARI model) used for experimental purposes 5.0 x 4.0 x 2.42 m. A rectangular cemented tank of size 4.0m x 3.0m x 1.7m was constructed inside the greenhouse. The effective water volume is 18 m³ with water depth level maintained at 1.5 m. The effective floor and water surface area of greenhouse are 20 m² and 12m², respectively. The volume of the greenhouse enclosure is 37m³. The brick wall of 0.25 m was constructed on the perimeter of floor area as the foundation of the greenhouse (Das and Tiwari, 2008)

Working Principle of Greenhouse Fish Pond System

During sunshine hours total solar radiation received by the greenhouse cover is partly reflected,

absorbed and transmitted inside the greenhouse. A large portion of inside radiation is absorbed by water. This is utilized in raising the temperature of water. The floor absorbs rest part of radiation. This absorbed thermal energy is conducted and convected into the ground and room air, respectively. During off sunshine hours, when room air temperature drops, a process of convective, evaporative and radiative heat exchanges takes place among floor, water and room air. This heat exchange is a form of long wave radiation, which is trapped inside the transparent greenhouse cover, and consequently heats up the room air, which in turn leads to the sudden fall in temperature. It has an advantage of being economic and easy to construct. The orientation of the greenhouse was from east to west direction. One exhaust fan was provided in the east wall of the greenhouse for forced ventilation. The schematic view of the experimental greenhouse is shown in Figure 2.

Basic Energy Balance

Assumptions

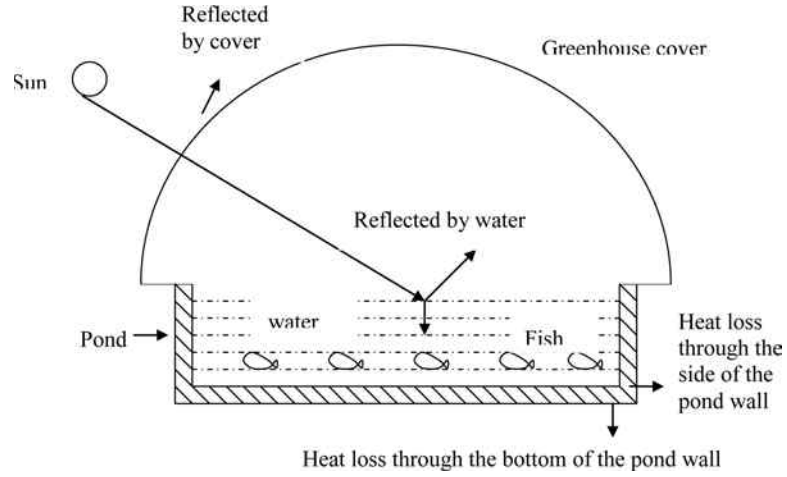
In order to write energy balance equation for the different components of the greenhouse the following assumption has been made:

1. Absorptive, heat capacity of the enclosed air, roof material, walls and tanks are neglected.
2. Heat flow is one dimensional in a quasi steady state condition.
3. Fish in the tank are less in number and small in size.
4. No water exchange during the experimentation.

Energy Balance Equation for Greenhouse Fish Pond System

The rate of energy absorbed by the water from the solar radiation is equal to the sum of the rate of energy stored in the pond water, the rate of

Figure 2. Experimental Quonset - shape greenhouse fish pond system



thermal energy losses by the pond water to the greenhouse air through conduction, convection and radiation and the rate of the thermal energy losses by the bottom wall and side wall of the pond to the earth.

$$\sum_{i=1}^8 \tau_i I_i A_i \sum \mu_j e^{n_j d} = M_w C_w \frac{dT_w}{dt} + h(T_w - T_r)A_w + U_b(T_w - \bar{T}_\infty)A_b + U_s(T_w - \bar{T}_\infty)A_s \quad (1)$$

Energy Balance Equation for Greenhouse air

The rate of thermal energy gained by the greenhouse air from the pond water through conduction, convection and radiation is equal to the rate of the over all heat loss from the greenhouse air to the ambient air in the atmosphere.

$$h(T_w - T_r)A_w = (UA)_{eff}(T_r - T_a) \quad (2)$$

Greenhouse Fish Pond with Flat Plate Collectors

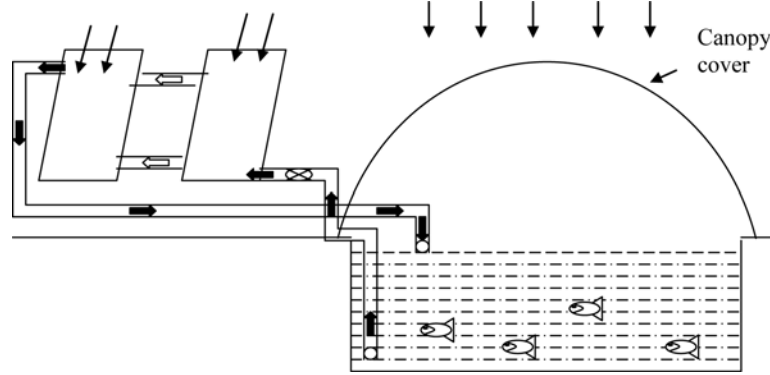
Experimental Set-up

The greenhouse fish pond system was connected to two numbers of flat plate collectors of area 2m² (1.0 x 2.0 m) each in series. The hot water was delivered to pond through gravitational force and cool water fed to collector with the help of a pump (Das et al., 2006). The line diagram of the experimental setup is shown in Figure 3.

Working Principle of GPS with Flat Plate Collector

The thermal energy absorbed by the pond water was increased by integrating two number of flat plate collectors in series. The greenhouse pond water is heated by both the direct heat gain from the solar radiation and also the heat absorbed from the flat plate collectors. The hot water was delivered to pond through gravitational force and cool water fed to collector with the help of a pump.

Figure 3. Experimental Quonset - shape greenhouse fish pond system with two numbers of flat plate collectors



Energy Balance Equations for Greenhouse Fishpond System with Flat Plate Collector

The sum of the rate of energy absorbed by the water from the solar radiation inside greenhouse fish pond system and the rate of energy absorbed by circulating the pond water through the flat plate collector is equal to the sum of the rate of energy stored in the pond water, the rate of thermal energy losses by the pond water to the greenhouse air through conduction, convection and radiation and the rate of the thermal energy losses by the bottom wall and side wall of the pond to the earth.

$$\sum_{i=1}^8 I_i \tau_i A_i \sum \mu_j e^{-n_j d} + \dot{Q}_u = M_w C_w \frac{dT_w}{dt} + h(T_w - T_r)A_w + U_b A_b (T_w - \bar{T}_\alpha) + U_s A_s (T_w - \bar{T}_\alpha) \quad (3)$$

where

$$h = h_c + h_{rw} + h_{ew}$$

$$\dot{Q}_u = NA_c [F_R (\alpha_0 \tau_0) I(t) \frac{(1 - (1 - k_k)^N)}{Nk_k} - F_R U_l \frac{(1 - (1 - k_k)^N)}{Nk_k} (T_w - T_a)]$$

For present case $N=2$ and during night hours $\dot{Q}_u = 0$.

Energy Balance Equation for Greenhouse Air

The rate of thermal energy gained by the greenhouse air from the pond water through conduction, convection and radiation is equal to the rate of the overall heat loss from the greenhouse air to the ambient air in the atmosphere.

$$h(T_w - T_r)A_w = (UA)_{eff}(T_r - T_a) \quad (4)$$

where

$$(UA)_{eff} = 0.33NV + \sum A_i U_i$$

$$\sum A_i U_i = A_1 U_1 + A_2 U_2 + A_3 U_3 + A_4 U_4 + A_5 U_5 + A_6 U_6 + A_7 U_7 + A_8 U_8$$

$$U_1 = U_2 = U_3 = U_4 = U_5 = U_6 = U_7 = U_8$$

Equation (3) can be rewrite as

$$T_r = \frac{(UA)_{eff} T_a + h T_w A_w}{(UA)_{eff} + h A_w} \quad (5)$$

Further, Equation (4) can be written as

$$h(T_w - T_r)A_w = (UA)_{eff1}(T_w - T_a) \quad (6)$$

where

$$(UA)_{eff1} = \frac{hA_w(UA)_{eff}}{(UA)_{eff} + hA_w}$$

Substituting Equation(6) in Equation(3) and after simplification, Equation(3) can be written in the form of first order differential equation as follows

$$\frac{dT_w}{dt} + a_1 T_w = f(t) \quad (7)$$

where

$$f(t) = \frac{\sum_{i=8}^8 \tau_i I_i A_i \sum \mu_j e^{n_j d} + 2A_c[F_R(\alpha_0 \tau_0) I(t) \frac{(1 - (1 - k_k)^2)}{2k_k} + F_R U_l \frac{(1 - (1 - k_k)^2)}{2k_k} T_a] + (UA)_{eff1} T_a + U_b A_b \bar{T}_\alpha + U_s A_s \bar{T}_\alpha}{M_w C_w} \quad (8)$$

$$a_1 = \frac{(UA)_{eff1} + U_b A_b + U_s A_s}{M_w C_w}$$

where

$$h_c = 2.8 + 3.0v$$

for $0 \leq v \leq 7$ m/s, (Watmuff et al., 1977)

$$h_{rw} = \frac{\varepsilon_{eff} \sigma [(T_w + 273)^4 - (T_r + 273)^4]}{T_w - T_r}$$

$$h_{ew} = \frac{16.273 \times 10^{-3} h_{cw} (P_w - \gamma P_r)}{T_w - T_r}$$

$$\varepsilon_{eff} = \left[\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_{gc}} - 1 \right]^{-1}, \varepsilon_w = \varepsilon_{gc} = 0.9$$

$$P(T_w) = \exp \left(25.317 - \frac{5144}{273 + T_w} \right)$$

$$P(T_r) = \exp \left(25.317 - \frac{5144}{273 + T_r} \right)$$

$$\sigma = 5.67 \times 10^{-8}$$

$$U = \left[\frac{1}{h_i} + \frac{1}{h_o} \right]^{-1}$$

$$h_i = 5.7 + 3.8v = 5.7$$

(if velocity of air inside greenhouse is taken zero)

$$h_o = 5.7 + 3.8v$$

$$U_c = \left[\frac{L_c}{K_c} + \frac{L_r}{K_r} \right]^{-1}$$

$$F_R = \left(\dot{m} C_f / A_c U_l \right) (1 - \exp(-\frac{A_c U_l F'}{\dot{m} C_f}))$$

$$k_k = (A_m F_{Rm} U_{Lm} / \dot{m} C_f)$$

Analytical solution of Equation(7) can be written as

$$T_w = \frac{\bar{f}(t)}{a_1} (1 - e^{-a_1 t}) + T_{wo} e^{-a_1 t} \quad (9)$$

where, T_{wo} is the water temperature at $t=0$ and $\bar{f}(t)$ is the average of $f(t)$ for the time interval 0 and t and a_1 is constant during the time. The water temperature of the pond for a particular time can be determined from this equation.

GREENHOUSE DRYER

Drying is simply the process of moisture removal from a product. It can be performed by various methods for a variety of different substances from solids to gases and even liquids (Hall, 1980). Drying is a process of heat and mass transfer simultaneously. Where, the heat energy applied to the crop is utilized to increase the temperature of it and to vaporize the moisture present in the crop through provision of latent heat of vaporization. The removal of moisture from the interior of the crop takes place due to induced vapor pressure difference between the crop and surrounding medium. The desired difference of vapor pressure may be obtained either by increasing the vapor pressure of the food surface or by decreasing the vapor pressure of the surrounding or by both. The convective heat transfer coefficient is an important parameter in drying rate simulation. Since, the temperature difference between the air and crop varies with this coefficient. The convective heat transfer coefficient was evaluated for some crops (green chillies, green peas, white gram, onions, potatoes, and cauliflower) under solar drying and developed a mathematical model for predicting the drying parameters (Anwar and Tiwari, 2001b);(Jain and Tiwari,2003);(Kumar and Tiwari, 2006). The dependence of convective heat transfer coefficient was further studied on the drying time during complete solar drying process of green peas and cabbage (Jain and Tiwari, 2004). Again the convective heat and mass transfer coefficients at different durations of the drying time of prawn (invertebrate) under the natural and forced convection of greenhouse drying was

determined. The heat transfer coefficient can be increased by providing forced convection drying (Das and Tiwari, 2008).

Design of Experimental Greenhouse Dryer

An even span roof experimental greenhouse dryer with effective floor area of $120 \times 0.78 \text{ m}^2$ was used for drying of prawn at IIT Delhi. The experimental greenhouse dryer for fish drying under natural and forced mode is shown in Figure 4 and Figure 5 respectively. The drying chamber constructed from a PVC pipe framework clad in a transparent ultraviolet (UV) stabilized polyethylene film of 150-200 micron thickness. A fraction of transmitted solar radiation absorbed partly by the fish, floor, exposed tray area and remaining solar radiation heats the enclosed air inside the greenhouse. A wire mesh tray of length 0.4 m and width 0.24 m was used to accommodate fish sample as thin layer. The orientation of the greenhouse dryer was fixed with east-west direction. The inclination of south and north roof was 25.90° . The central height and sidewalls were raised to 0.60 and 0.40 m, respectively. For forced convection a fan of 120mm sweep diameter with air velocity 5m/s was provided on the sidewall of the greenhouse during the experiments. (Das and Tiwari, 2008).

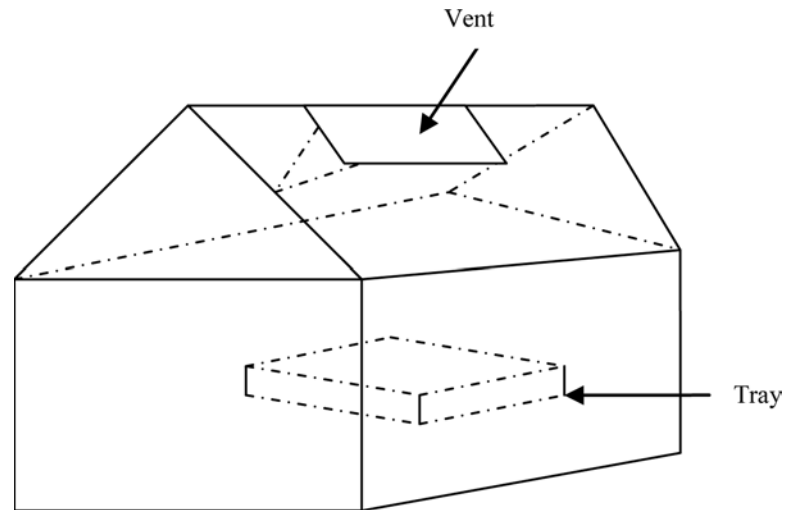
Drying under Natural Mode

Two vents each of $0.2 \times 0.1 \text{ m}^2$ were made on the south and north roof for natural ventilation purposes during over heating inside the greenhouse. (see Figure 4)

Greenhouse Drying under Force Mode

In case of forced mode greenhouse dryer a fan of 120 mm sweep diameter with rated air velocity 5m/s was provided on the east wall of the greenhouse during the experiments of forced convection. It helps to remove the excess rela-

Figure 4. Experimental set-up for prawn drying inside greenhouse (Source: Das & Tiwari, 2008)



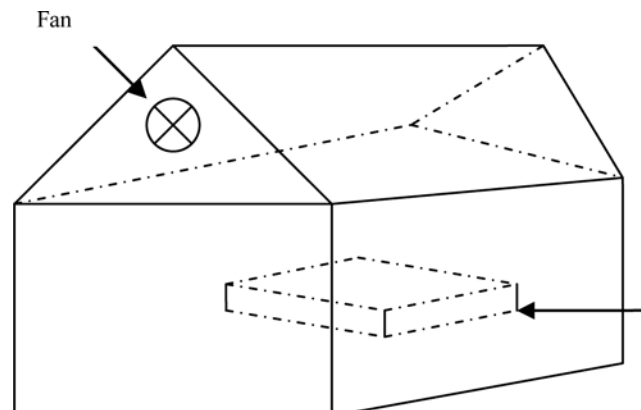
tive humidity inside the greenhouse apart with the above assembly.

Experimental Observation

Indian minor carp prawn (*Macrobrachium lamarrei*); invertebrate was considered for drying in greenhouse. The fresh fish purchased from local market was washed with fresh water. Surface water was removed by blotting with absorbent paper. A steel wire mesh tray of $0.25 \times 0.20\text{m}$ was used during drying of the fish. The fish were arranged

in a single layer in the drying tray. The tray with fish was kept on the measuring balance. Experiments were conducted in July 2006 between 8:00 and 17:00 h for forced drying and 10:00 to 17:00 for natural drying under the composite climate of New Delhi, India. The solar radiation ranged during these hours between 150 and 900 W/m^2 .

Figure 5. Experimental set-up for prawn drying inside greenhouse under forced convection model (Source: Das & Tiwari, 2008)



Computation Procedure to Determine the Convective Heat Transfer Coefficient

Convective Heat Transfer Coefficient (Natural and Forced)

The values of convective heat transfer coefficient can be obtained using the following expression:

The Nusselt number Nu under natural convection is a function of Grashof Gr and Prandtl Pr numbers.

$$Nu = \frac{h_c X}{K_v} = C (Gr Pr)^n \quad (10a)$$

The Nusselt number Nu under natural convection is a function of Reynolds number (Re) and Prandtl Pr numbers.

$$Nu = \frac{h_c X}{K_v} = C (Re Pr)^n \quad (10b)$$

Now, the natural and forced convective heat transfer coefficient is determined by using the following expression obtained from Equation(10a and b) where, Gr , Pr and Re can be evaluated at mean vapor temperature by using the expression given below,, h_c is the convective heat transfer coefficient in $W/m^2 K$; X is the characteristics length in m; K_v is the thermal conductivity of the humid air in $W/m K$ and C and n are the constants of Equation(10a).

Grashof number (Gr)

$$= \frac{g\beta' X^3 \rho_v^2 \Delta T}{\mu_v^2} = \frac{buoyancy\ force}{viscous\ force}$$

Prandtl number (Pr)

$$= \frac{\mu_v C_v}{K_v} = \frac{momentum\ diffusivity}{thermal\ diffusivity}$$

Reynolds number (Re)

$$= \frac{\rho_v v X}{\mu_v} = \frac{inertia\ force}{viscous\ force}$$

Therefore, the convective heat transfer coefficient can be determined by using the expression given in Equation(10) for the Nusselt number as

$$h_c = \frac{K_v}{X} C (Gr Pr)^n \quad (11a)$$

$$h_c = \frac{K_v}{X} C (Re Pr)^n \quad (11b)$$

The rate of heat utilized to evaporate moisture is given as (Malik et al., 1982)

$$Q_e = 0.016 h_c [P(T_f) - \gamma P(T_r)] \quad (12)$$

where, $\dot{Q}_e$ is the rate of heat utilized in J/m^2s ; $P(T_f)$ and $P(T_r)$ are the partial vapor pressures of air at the temperatures in $^{\circ}C$ of the fish surface T_f and inside greenhouse T_g at relative humidity γ , respectively.

Where $P(T) = \exp(25.317 - \frac{5144}{T + 273})$
(Fernandez and Chargoy, 1990)

Substituting h_c from Equation(11), then Equation(12) becomes surrounding humid

$$Q_e = 0.016 \frac{K_v}{X} C (Gr Pr)^n [P(T_f) - \gamma P(T_r)] \quad (13a)$$

$$Q_e = 0.016 \frac{K_v}{X} C (Re Pr)^n [P(T_f) - \gamma P(T_r)] \quad (13b)$$

The moisture evaporated (m_{ev}) in kg is determined by dividing Equation(13) by the latent heat

of vaporization (λ) and multiplying by the area of the container (A_c) and time interval (t) in s.

$$m_{ev} = \frac{Q_e}{\lambda} A_c t = 0.016 \frac{K_v}{X\lambda} C (Gr Pr)^n [P(T_w) - \gamma P(T_r)] A_c t \quad (14)$$

Rearranging the terms and Equation (14) becomes

$$\frac{m_{ev}}{Z} = C (Gr, Pr)^n \quad (15a)$$

$$\frac{m_{ev}}{Z} = C (Re, Pr)^n \quad (15b)$$

where,

$$Z = 0.016 \frac{K_v}{X\lambda} [P(T_f) - \gamma P(T_r)] A_c t$$

Taking logarithm of both sides of Equation(15),

$$\ln \left[\frac{m_{ev}}{Z} \right] = n \ln (Gr, Pr) + \ln C \quad (16a)$$

$$\ln \left[\frac{m_{ev}}{Z} \right] = n \ln (Re, Pr) + \ln C \quad (16b)$$

Equation (16a and b) is the analogy of a straight line equation,

$$Y = b_1 X + b_0$$

where, b_1 and b_0 are the independent and dependent variables.

$$Y = \ln \left[\frac{m_{ev}}{Z} \right], \quad b_1 = n,$$

$$X = \ln (Gr Pr) \text{ and } b_0 = \ln C$$

$$X = \ln (Re, Pr)$$

Thus,

$$C = e^{b_0} \quad (17)$$

Once the numerical values of the constants C and n are known, the convective heat transfer coefficient can be computed by Equation(16) and using measured values of the ambient air, inside greenhouse air, surface temperature of fish and relative humidity in greenhouse condition during a given time period.

Convective Mass Transfer Coefficient

The convective mass transfer coefficient can be determined using the relation

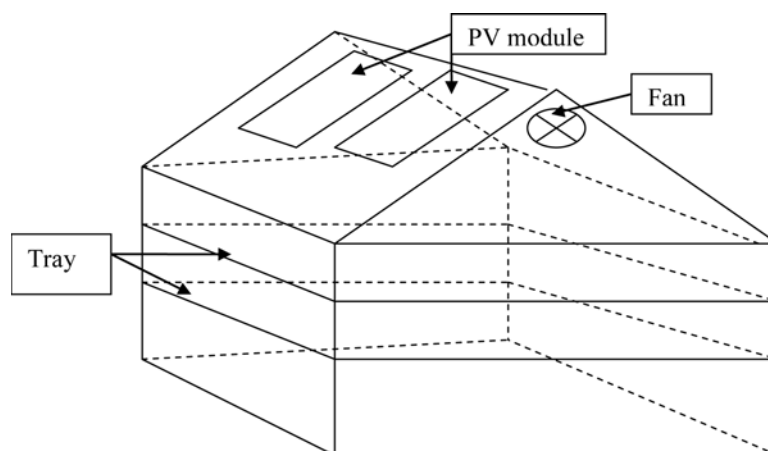
$$h_c = \frac{\dot{Q}_e}{T_r - T_f} \quad (18)$$

where, h_c is the convective mass transfer coefficient in $W/m^2 K$, $\dot{Q}_e$ is the rate of heat utilized in $J/m^2 s$, greenhouse air temperature (T_r) and, T_f is the average of fish temperature (T_f) just above the fish surface.

Computation Technique

The average surface temperature of fish $\bar{T}_f$ and inside greenhouse temperature above the fish surface $\bar{T}_r$ were calculated at hourly intervals for corresponding moisture evaporated. The physical properties of humid air were evaluated for the mean temperatures of $\bar{T}_f$ and $\bar{T}_r$. These physical properties were utilized for calculating the values for the Grashof Gr , (Pr) Prandtl numbers and (Re) Reynolds numbers. The values of C and n in Equation (11) were obtained by linear regression

Figure 6. Hybrid photovoltaic-thermal (PV/T) integrated greenhouse dryer



analysis expressed in Equation(17) at the increment of every hour of observation and thus the mean values of h_c were computed at the corresponding hour of drying.

Hybrid Greenhouse Dryer

Experimental Greenhouse Dryer

An even span greenhouse of 1.8 m and 1.05 m central and side wall height respectively was integrated with two PV modules (glass to glass; dimensions: 1.20 m $\times$ 0.55 m $\times$ 0.01 m; 75 Wp each) at the south roof was used for the drying of grapes. The DC electrical power produced by the PV modules was used to run the fan (inner diameter = 0.080 m, outer diameter = 0.150 m) under forced convection drying and also provide thermal heating of the greenhouse. To provide air movement in the greenhouse dryer, 0.15 m height is open at bottom side and further 0.10 m is provided with wire mesh. The air moves from bottom to top through three-tier system of perforated wire mesh trays as the air at bottom becomes hot. The material of the greenhouse dryer cover is UV stabilized polyethylene sheet, which prevents unnecessary circulation of ambient air and thus maintains the desire temperature inside the greenhouse. The

developed hybrid photovoltaic-thermal (PV/T) integrated greenhouse dryer is shown in figure 6. (Barnwal and Tiwari, 2008)

Working Principle

The air moves from bottom to top through three-tier system of perforated wire mesh trays as the air at bottom becomes hot. The UV stabilized polyethylene sheet has been fitted over the structural frame of the dryer which helps in trapping of infrared radiation. It also prevents unnecessary circulation of ambient air and thus maintains the desire temperature inside the greenhouse.

CONCLUSION

Use of different solar thermal applications is a good alternative to the conventional heat requirement for different purpose inside greenhouse for the production of agricultural crop. Greenhouse fishpond system is a good option to increase the production than open pond system. Indirect heating with flat plate collector is a useful tool, where direct or passive heating is not sufficient for heating the pond water. Greenhouse dryer can be used to dry several agricultural crops. The heat

transfer coefficient can be increased by providing forced convection drying. Convective heat transfer coefficient was a function of physical properties of moist air, operating temperature and surface area.

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KEY TERMS AND DEFINITIONS

Forced Convection: Heat convection caused by external sources such as pump etc is known as forced convection or forced mode.

Greenhouse Dryer: Greenhouse structure used for drying is called greenhouse dryer. Inside greenhouse dryer crops are dried using the solar thermal energy.

Greenhouse Fishpond System: The system where greenhouse structure with a fish pond system inside is used for the cultivation of fish is known as greenhouse fish pond system.

Greenhouse: Greenhouse is a building where plants are grown.

Hybrid Greenhouse Dryer: Greenhouse dryer which include photovoltaic thermal hybrid collectors for the drying of crop is known as hybrid greenhouse dryer. Hybrid PV/T system converts solar radiation into thermal and electrical energy.

Natural Convection: Natural convection is the type of heat transport or circulation of air which is generated by thermal and density effect not by external source.

Solar Thermal Application: Applications where solar thermal energy is used.

Thermal Analysis: Thermal analysis is a branch in material science where properties of material are studied with the change of temperature.

APPENDIX: NOMENCLATURE

Table A.

A	Area, m ²
A_c	Area of fish (tray), m ²
b	breadth, m
C	constant
C_w	specific heat of water, J/ kg K
C_v	specific heat of humid air, J/ kg K
C_f	specific heat of fish, J/ kg K
F_R	Flow rate factor
H	total heat transfer coefficient from water to greenhouse, W/(m ² K).
h_c	convective heat transfer coefficient of fish, W/(m ² K).
h_{cw}	convective heat transfer coefficient of water, W/(m ² K).
h_{ew}	evaporative heat transfer coefficient of water, W/(m ² K).
h_{rw}	radiative heat transfer coefficient from water to sky, W/(m ² K).
h_o	Parameter depends on convective heat transfer coefficient, mass of air and water, Partial pressure, Specific heat of air and latent heat of water.
$I(t)$	total solar intensity falling on greenhouse, W/(m ² K).
I_b	beam radiation, W/m ² K
K	thermal conductivity of ground, W/(m ² K).
K_v	thermal conductivity of humid air, W/(m K).
L	Length of greenhouse, m
M	mass, kg
m	flow rate of water mass, kg/sec
m_{ev}	moisture evaporated, kg
N	number of air charges per hour in greenhouse
N	coefficient
Nu	Nusselt number ($=h_c L/K_v$)
Pr	Prandtl number ($=\mu_v C_v/K_v$)
$P(T)$	Partial vapor pressure at temperature T , N/ m ²
P_w	saturated vapor pressure at water temperature (Pa)
P_r	saturated vapor pressure at greenhouse air temperature (Pa)
Q_e	Rate of heat utilized to evaporate moisture, J/ m ² s
Re	Reynolda number ($=\rho_v v d / \mu_v$)
T_f	surface temperature of fish, °C
T_e	temperature of humid air above the fish surface, °C
T_i	average of fish and humid air temperature, °C
T	time, s
T	temperature, °C

continued on following page

Greenhouse Solar Thermal Application

Table A. Continued

U_b	Overall heat transfer coefficient from bottom to earth, W/m ² K
U_s	Overall heat transfer coefficient from the side to earth, W/m ² K
U_L	Overall heat transfer coefficient from greenhouse to ambient through top, W/(m ² K).
V	velocity of air, m/s
V	volume of greenhouse, m ³
X	characteristic dimension, m
μ_v	dynamic viscosity of humid air, kg/ ms
ρ_v	density of humid air, kg/ m ³
Subscripts	
a	air or ambient air
g	ground in greenhouse
<i>eff</i>	effective
w	water
th	thermal
Greek letters	
α	absorptivity (decimal)
τ	transmitivity of greenhouse cover, dimensionless
γ	relative humidity(decimal)
ε	emissivity, dimensionless
ρ	density, kg/m ³
σ	Stefan-Boltzman constant (5.67x10 ⁻⁸ W/m ² K ⁴)
α	Infinity (ground at lager depth)
λ	latent heat of vaporization, J/ kg

Chapter 18

Technology Selection for Solar Power Generation in the Middle East: Case of Saudi Arabia

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ABSTRACT

Saudi Arabia is moving towards economical and technological development and to be an active player in the dynamics of the international community. The economic growth in the country requires significant additional electrical power generation in order to supply this increasing demand. At present, fossil fuel (petroleum and natural gas) reserves in Saudi Arabia are reliable in terms of feeding the needs of its conventional power plants. Fossil fuels, however, are not sustainable, are subject to eventual depletion and plants using these fuels produce large amounts of CO₂ emissions. The authors have examined other power generation alternatives with an eye towards achieving sustainability. These requirements have led them to propose a renewable energy source—radiant energy from the sun as the way to achieve long-term success. The region is blessed with an abundant solar flux throughout most of the year. Recognizing this, the authors propose building solar-powered electrical generation plants in the Saudi deserts, but are faced with the problem: “Which solar technology is the ideal choice for this application?”

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Several different technologies have been identified and analyzed. A mathematical model was constructed and used to make a selection of the optimal technology. The decision model employed to determine the optimal technology, taking account of the fact that in making such a technology selection subjective judgment is required, is the Hierarchal Decision Model (HDM). This research relied on data extracted from scientific journals and industry sources as the inputs for the Decision Model. The authors also validated their research and derived expert opinion weighting factors with international experts in the solar technology. They have applied the model to a case study to demonstrate the use of it.

INTRODUCTION

Terrestrial solar energy is abundant, estimated at 174 petawatts (10^{15} watts) of energy, or a flux of approximately 340 W/m^2 on the surface of our planet every day¹. This is an average, however, and the actual values vary from one region to another.

Saudi Arabia has an oil-based economy, possesses more than 20% of the world's proven petroleum reserves, and ranks as the largest exporter of petroleum. Currently, all electrical power generation in Saudi Arabia is petroleum or natural gas-based. In 2008, revenues from worldwide high oil prices have led to increased economic growth. In December 2005, after many years of negotiations, Saudi Arabia joined the World Trade Organization (WTO) as part of its effort to attract foreign investment, develop the industrial sectors, and diversify the economy. In response, Saudi Arabia has begun to develop six economic cities which are project to play a role in the future of the country's economy. The government is encouraging private sector growth - especially in power generation, in order to satisfy the growing demand for energy, and to increase employment opportunities for the growing Saudi population. As a result of the accelerated economic growth and industrial expansion, the electrical power demand is expected to double in the next decade, which raises the issue of finding more sustainable and scalable technologies to produce electricity and to boost the country's capabilities of producing and distributing electricity. Furthermore, threat of eventual depletion of its fossil fuel resources, is another major obstacle that is compelling the

country to secure alternative energy resources. The main alternative natural renewable energy source which is abundantly available in Saudi Arabia is solar. The power in the solar radiation, which reaches the earth, if it can be reliably and efficiently converted to electricity, is sufficient to make significant contributions to the Kingdom's energy supply. Our research, therefore, contains a suggestion for the country's decision makers to be opportunistic and to think sustainably and grow the country's economy reliably by investing and building the future renewable energy plants which rely on solar power.

METHODOLOGY BACKGROUND

Hierarchical models have been used for evaluation of alternatives in many parts of the energy sector: Aminloei and Ghaderi (2010) for generation planning in Iranian power plants; Aragones-Beltran (2010) for the selection of photovoltaic solar power plant investment projects; Chatzimouratidis et al. (2008) for the evaluation of power plants' impact on living standards; Chen (2009) for eco-efficiency; Dey (2002) for cross-country pipelines; Garcia et al. (2008) for evaluation of an electric distribution system; Jaber et al. (2008) for the evaluation of conventional and renewable energy sources for space heating in the household sector; Kahraman et al. (2009) for evaluation of renewable energy alternatives; Karger and Hennings (2009) for sustainability evaluation of decentralized electricity generation; Nagesha and Balachandra (2006) for energy efficiency,

Onut et al. (2008) for energy resources for the Turkish manufacturing industry; Wijayatunga et al., (2006) for cleaner generation technologies; Quintero et al. (2008) for comparative analysis for fuel ethanol production from sugarcane and corn; Thorhallsdottir (2007) for evaluating and ranking national energy projects by environmental impact; and Vashishtha and Ramachandran (2006) for demand side management implementation strategies in the Indian power sector.

The HDM provides a powerful tool for valuing different types of energy generation technologies. The selection of evaluative criteria, was initiated by carrying out literature research. The selection could have been done only with research but, we went further and supplemented the literature data by consulting with electrical power generation experts in Saudi Arabia (SA). Our theory was that the local expertise would add value to picking the right criteria. Based on the feedback from these experts and the literature results, we have selected five criteria:

- Efficiency
- Technology Maturity
- Environmental Impact
- Life Time
- Cost

Efficiency here is defined as the conversion efficiency (watts of electrical power generated/watts of solar energy consumed) for each technology. Technology Maturity determines the current level of commercialization with respect to each technology. Photovoltaic Cells, later in our report emerged as a leader from that aspect. Since the key point of moving towards a renewable energy is to minimize the impact on the environment, the experts' suggestion of using environmental impact as criteria makes perfect sense. Longevity of any technology is important, when it comes to large-scale infrastructure setup. The Lifetime as a criterion serves the purpose to understand the operational time limitations which each technology

exhibits, compared with competing technologies. Finally, Cost is another key criterion, which cannot be overlooked in our decision-making. There were several costs involved here. Installation Cost, Storage Cost, Transmission Cost, Maintenance Cost and the Cost to generate electricity get added to the overall implementation cost of the technology. To sum up, our basis of selecting the criteria was based on local expertise. Their choices approximately matched those resulting from our Literature research.

DECISION MODEL

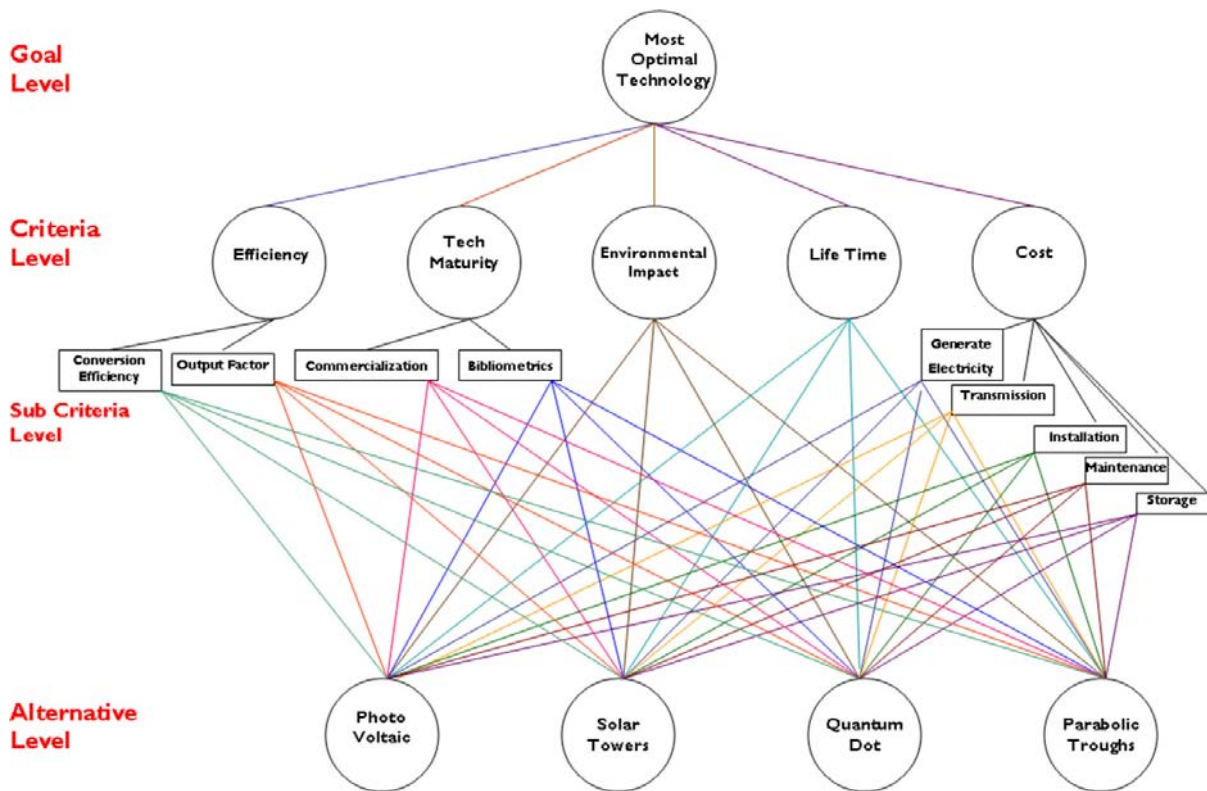
The purpose of the Hierarchical Decision Model, presented in Figure 1 below, is to select the most optimal solar technology for SA. This selection is based on weighted importance of the characteristics of efficiency, technology maturity, environmental impact, life time and Cost. Three of the five characteristics or criteria were further sub-categorized. Conversion Efficiency and Output factor were considered under Efficiency. Commercialization and Bibliometrics were considered under Technology maturity. Cost was divided into five sub-criteria as Electricity Generation Cost, Transmission Cost, Installation Cost, Maintenance Cost and Storage Cost. These criteria and sub-criteria were researched for each of the four technologies in order to have a fair comparison of the technologies.

REGIONAL BACKGROUND

Economic Situation and Energy Demand in Saudi Arabia

In any country the electric power sector is highly interrelated with the economic environment under which it operates. For that reason, the economic characteristics and fundamentals of the economy need to be considered while studying the power

Figure 1. Hierarchical decision model



sector of any country. In the past, According to Saudi Aramco forecasts, natural gas demand in the kingdom is expected nearly to double to 14.5 billion cubic feet per day (Bcf/d) by 2030, up from an estimated 7.1 Bcf/d in 2007 (DOE, n.d.a). With this huge economic boom the country's economic reforms has also kept pace and witnessed major boost in foreign direct investments over the last few years. In December 2005, Saudi Arabia became the 149th member of the WTO after over 12 years of negotiations (SUSRIS, n.d.). Since joining the WTO, Saudi Arabia has taken a series of measures to improve the country's investment climate: eliminate obstacles facing private investors, allow foreign manpower recruitment and speeding up licensing procedures.

Regarding the development of infrastructure facilities, Saudi Arabia will have a total of six special economic zones with the addition of the three zones to be announced later this year.

Saudi Arabia will require at least US\$600bn in investment over the next 20 years, according to Saudi Arabian General Investment Authority (SAGIA) including US\$170bn alone in electricity generation and water desalination capacity (Saudi Electricity Company, 2006). It is estimated that additional investment would be needed for petrochemicals, ports, highways and railways, and another IT-related businesses, such as life-sciences and healthcare. It is projected that the current economic expansion is probable to continue at least till 2010 as several large scale projects are going to be implemented in the next five years. Thus, the economy of Saudi Arabia is on a path of high growth as a result of strong oil revenues which, in turn, will mean a record budget and current economic surplus, continued reduction of government debt and strong growth in spending by the government.

According to the Saudi Electricity Company (SEC)(2007) the total available capacity achieved in 2007 exhibited a growth rate of 6.1%, bringing up the total available capacity to 36,949 MW, compared with 34,823 MW in 2006. While the average annual generation of electricity in 2007 reached 32,600 GWH compared with 30,300 GWH in 2006. In response to that, the SEC is implementing several projects to boost the electrical generation capability in order to meet the forecasted demand. These projects introduced several generation plants that run on diesel, and mainly natural gas in order to free up more oil for export usage (DOE, n.d.b). Undeniable, the increasing need for electricity generation is associated with other factors such as high seasonal demand n, economic growth, infrastructure development, and increasing industrial development. As a result, the SEC conducted several projects which include building new power plants throughout the country to increase its generation capacity as well as simultaneously upgrading its electrical power transmission system capability. In this context, the total project expenditure in the areas of electric power generation, transmission, and distribution reached \$ 3,590 million at year-end 2007, bringing the total costs of projects implemented since the

establishment of the Company in the year 2000 to \$ 25,051 million. This includes projects that are still under implementation. Moreover, the Company's 2008 budget includes a number of new projects in power generation, transmission, and distribution amounting to \$ 7,371 million (Saudi Electricity Company., 2007).

Solar energy utilization in Saudi Arabia is currently only being used for small scale projects for the sake of experimenting and gathering data on solar radiation and its potential as an alternative electrical power source for the country. The Energy Research Institute (ERI) at King Abdulaziz City for Science and Technology (KACST), developed the Saudi Atlas Project which was initiated in 1994, as a joint R&D project between the ERI and the National Renewable Energy Laboratory (NREL) of the U.S. Twelve locations in the following cities throughout the country were carefully selected (Said et al., n.d.). The total solar energy capability is 4 MW and these capabilities are installed in different location across the country.

In the recent years, solar energy has become a major concern for electricity production. The Country's decision makers are investing heavily to advance this technology and showing a great deal of evident enthusiasm for such an energy

Table 1. Location of solar projects in SA

Location	Capacity	Applications
Solar Village	350 kW PV System (2155 MWh)	AC/DC electricity for remote areas
KAU, Jeddah	2 kW solar hydrogen (50 kWh)	Testing of different electrode materials for solar hydrogen plant
Solar Village	3 kW PV test system	Demonstration of climate effects
Southern SA	4 KW PV system	AC/De electricity for remote areas
Sadous Village	PV water desalination (0.6m ³ /hr	PV/RO interface
Muzahmia	PV in agriculture (4 kWph)	AC/Dc grid connected
12 stations	Solar radiation measurement	Saudi solar atlas
5 stations	Wind energy measurement	Saudi solar atlas
Al-Hassa, Qatif	Solar dryers	Food drying (dates, vegetables, etc.)
Dammam	Energy management in buildings	Energy conservation
Solar Village	Solar collectors development	Domestic, industrial, agricultural

source. That is perhaps because they have realized the need for a long-term reliable and secure source of energy. Also, increasing investments in mining technologies for fossil fuels will accelerate their depletion and boost climate change, while better solar technology will be beneficial for the future. While renewable energy is a promising solution for the near future in generating electricity, there is a significant negative aspect of its relatively high installation and operating cost and low operational efficiency. If solar energy is the future, Saudi Arabia and the nations of the Middle Eastern Sun Belt will enjoy a disproportionate slice of the pie of the world's energy resources tomorrow as much as they do today.

Alternate Electrical Power Generation

In this section, we discuss five alternative sources to generate electricity and assess their viability. The following resources have been considered:

1. **Hydroelectric:** Saudi Arabia with its huge desert is lacking natural flowing water as there are no rivers or natural reservoirs to be utilized for electricity generation.
2. **Wind Energy:** Although wind energy has a potential in Saudi Arabia and has been experimented in 20 different areas, it is still unreliable for such application due to a lack of continuous strong wind currents.
3. **Geothermal:** Saudi Arabia indeed has huge geothermal potential, but this potential has not been exploited to date, for electricity usages.
4. **Nuclear Power:** it is associated with high investment to be implemented for large application and it needs a highly trained personnel and institutions.
5. **Solar Rnergy:** Solar energy seems to be the solution for large scale power generation as Saudi Arabia has a huge potential with the enormous solar flux in its region.

Saudi Arabia sits on the eastern edge of the so-called Sun Belt, which stretches across the deserts of northern Africa and the Persian Gulf. Saudi Arabia is listed on the map of the top five places for potential photovoltaic generation of electricity around the world (Norris, n.d.). Saudi Arabia is one of the most powerful sunlight absorbers in the world: 105 trillion kilowatt hours a day, which is the equivalent of 10 billion barrels of crude oil in energy terms (Royal Embassy of Saudi Arabia, n.d.). The average annual solar radiation falling on the Arabian Peninsula is then about 2200 kWh/m²/day (Said et al., n.d.). These figures highlight the fact that solar radiation is uniquely available in all the areas of Saudi Arabia at high intensity all year round. This makes Saudi Arabia one of the most likely candidates for a country run in the future primarily by solar energy. However, effective utilization of solar energy in Saudi Arabia has not yet made reasonable progress mainly due to several obstacles, some of which are listed as follows (Alawaji, 2001):

1. The wide availability of petroleum, and its current status relative to solar energy as a source of energy and its relatively low cost
2. A significant dust hazard due to blowing, which in some parts can reduce solar energy by 10—20%.
3. The availability of governmental subsidies for oil and electricity generation and non-availability of similar subsidies for solar energy programs.

Demand in Solar and Large Scale Systems in Developing Countries

Ever since the discovery of solar energy generation, mankind has been interested in learning more and more about the nature of this technology. Starting from heating water systems and drying crops to the development of the photovoltaic cells to generate the electricity directly from the

sun, the question asked is: has utilization of the solar energy reached its maximum potential? Especially in view of the future prospect of fossil fuel depletion measures taken to reduce CO₂ emissions into the atmosphere and to protect our environment, the revolutions and initiatives from different sectors from residential to commercial, countries and governments, all pinpoint sustainability and green sources of energy as the hottest topics in any energy related discussion.

Solar energy photovoltaic perfectly embodies the various goals listed above. Generating electricity directly from the sun produces no pollution during operation, it utilizes a free and universally available resource (the sun) solar PV and provides a cheap and long term source of electricity that is independent of consumable fuel cost increases (Solarbuzz, 2008).

The sun is a promising and inexhaustible source of energy. Its feasibility has been proved and used for several decades as it has been seen as viable for the operation of stand-alone devices such as solar cell and photovoltaic (PV), however, the remaining question in people's minds is: "Is solar a viable alternative energy source on a mass scale?" The increasing proliferation of large scale solar power plants worldwide seems to suggest that the renewable solar energy does indeed have a promising future.

Global demand for energy is projected to increase 30% or more by the year 2030, while energy demand in developing countries is likely to double in that time (Arvizu, 2007). As the search for renewable energy rapidly grows, several alternatives to fossil fuel and other deleterious energy sources, have emerged. Some examples are wind generation, ocean wave or tidal generation, and geothermal generation. None of these are currently as applicable in developing countries to sustainable generation of electricity as solar power generation. Solar technologies are promising candidates to produce a significant increase of electrical power generation in many developing country locations

for the following reasons (Foroudastan & Dees, 2006):

1. Most developing countries are located in regions with optimal access to solar radiation.
2. The lack of energyproducing resources in the developing countries is directly affecting their ecosystem which will eventually result in social decline.
3. The trend towards increasing global dependence on fossil fuel accelerates the need for alternate energy generation technology which will eventually lead to an increase in the competition and lowering the price.
4. Solar energy generation holds the promise of low-cost electricity over time which in turn would be considered as a vital factor to boost the economy and to support the needs for future developmental projects.
5. Decrease the unemployment rate and increase the efficiency of energy industry related training and educational centers.

THE TECHNOLOGY OPTIONS

Large-scale (multi megawatt) solar electrical power generation plants are an obvious solution to satisfy this need; however, the question of which specific energy conversion technology is optimum for this application has not previously been solved. In this study, the following technologies are considered: 1) Parabolic-Trough Concentrators which produce steam to drive turbine-driven generators, 2) Tracking Helio-Concentrator Solar Towers which also produce steam. 3) Silicon based-Photovoltaics- the direct conversion of solar energy into electricity, 4) Quantum Dot Solar cells which are a refinement of the material/geometry used for photovoltaics, and 5) Solar Ponds which utilize a brine solution to passively absorb sunlight and generate heat to drive steam driven turbine generators

Parabolic Trough Concentrators

In this method¹, incoming solar energy is focused on a linear pipe (which carries a heat transporting fluid); through the use of a mirror that is shaped in a linear trough whose cross section is a parabola². The heat transporting fluid absorbs the incident solar radiation resulting in an operating temperature of close to 400° C, and is piped through an absorbing pipe placed at the focal point of the mirror. The mirror's cross section allows it to track the sun over a wide range of incident angles without any physical motion of either the absorbing pipe or the mirror.

The system is relatively easy to install, maintain and clean. Heat is extracted by the transportation fluid, and then is used to generate steam. The steam is converted to electrical energy through a conventional steam turbine. The parabolic trough can be used along with a combined cycle of steam turbine. Parabolic trough systems represent the most mature solar thermal technology having been proved feasible in a 354 MW plants connected to the grid since 1980 in Southern California installation that has been producing electricity at a cost of from \$0.08-0.13/kW (Pilkington Solar International, 1996)

Improvements in these systems are ongoing such as an advanced structural design aimed at improving the optical accuracy of the system and will lead to further cost reductions. One of the major issues of the parabolic troughs systems is the thermal losses in the receiver's tubes. Improvement in the tube design will increase the operating temperature and thus will lead to better conversion efficiency. Trough technology is a mature and clean solar power solution with years of successful power generation behind it. Troughs have been in use since the 80s with outstanding results. The technology has been improving steadily for the last 30 years, and modern troughs operate more efficiently at lower cost. Today³, there is more than 300 MW of concentrated solar power or "CSP" trough power in operation around the world, with

400 MW under construction and around 6 GW in development (Abengoa Solar, n.d.)

Tracking Helio-Concentrating "Tower Power"

In this system, a field of mirrors mounted on sun-tracking structures (heliostats), concentrate the incoming solar energy onto a single central tower. The system uses a molten salt to transport the thermal energy from the tower which heats to over 1000°C, to a steam generator which in turn drives a turbine electrical generator. (ABS Energy Research, n.d.)

This technology is mostly in the demonstration phase, although an 11MW commercial plant has been constructed near Seville Spain, and has been operating successfully since 2007⁴. More feasibility is expected within the next few years. The theoretical models have proved a feasibility of providing 200MW of electricity using this technology giving the solar tower technology long-term prospects for higher conversion efficiencies.

Concentrating Solar Power (CSP) is a term for a group of technologies that use a reflective surface for concentrating solar irradiation on an absorber. Concentrated Solar Power Plants (CSP) technology is a revolution in the solar energy field in the past few decades for their proved technological feasibility (some of them) to their promise of bringing a clean energy at a large scale. They basically superheat a working fluid to extremely high temperature then route the hot fluid to a boiler to produce steam which is used in a steam turbine to generate electricity. This operation offers superior conversion efficiency (ratio of output of electrical power to input irradiance) (Kooie, 2005) especially in certain locations that sun irradiance is considered adequate through the day time. This process can be achieved either by using Parabolic Trough, Solar Tower the following table shows the main characteristics of some examples of the CSP technology (Price et al., 2007).

Table 2. CSP technology parameters

Parabolic Trough		Solar Tower
Size Range	30-354 MW	10-200 MW
Peak Efficiency	25-30	30
Technology Development risk	Commercially available	Scale-up Demonstration
Storage available	Yes	Yes
Hybrid design	Yes	Yes

Given the purpose of the study is being limited to study the feasibility of projecting solar power plant within the next few years, the above CPS technologies are considered good candidates for it. Nevertheless it was decided to choose the CSP technologies for:

1. It promises clean energy due to the feasible commercialization.
2. Higher electricity production capacity.

Risk involved in the investment is too low.

Silicon Based Photovoltaic

The first photovoltaic panels were invented by Bell Laboratories in 1954 (Mayfield, 2008). Modern solar panels are generally made from semiconductor materials (most commonly crystalline-silicon, amorphous-silicon, and thin film). A junction between p- and n-type semiconductor materials produces an electric field that collects the electrons excited when the materials are being struck by sunlight. The resulting current can then be used in an external circuit. A Photovoltaic module is made up a number of PV cells and several layers and they can be combined into arrays of similar voltages. Solar cells are usually made of several semi-conducting materials, which have a limited ability of conducting the electrical current through the. The uniqueness of these materials that they are suitable to produce electricity from sunlight which generate what called "Photovoltaic effect". The most common semi-conducting

material used is silicon which is the second most common element in the earth's crust. Solar cells can be made from a number of semi-conducting materials. (Mayfield, 2008).

The performance of Photovoltaic cells is quantified in terms of their efficiency of converting the sunlight into electricity. The conversion process is subjected to constraint directly related to the wavelength and the photon energy of the sunlight rays, only certain energies will work efficiently to create electricity, and the rest of it will be either reflected or absorbed as heat by the material that makes up the cell. The down side of this process is its very low efficiency. A typical PV has an efficiency of 15% and low efficiencies require larger arrays which leads to higher cost. Improving solar cell efficiencies while holding down the cost per cell is an important goal of the PV industry, NREL researchers, and other U.S. Department of Energy (DOE) laboratories, and they have made significant progress. The first solar cells, built in the 1950s, had efficiencies of less than 4%. (NREL, 2009)

There are several methods of installation of PV panels; they can be installed on the roof of a building or on the ground for either residential or commercial application of electricity generation. PV cells can be used in the tracking system in large-scale electricity generation station that allows the PV arrays to adjust their direction in order to optimize electricity production throughout the course of the day.

Primarily, the photovoltaic technology was used for non-grid purpose using small-stand

alone cells to generate electricity. In 1992, non-grid usage of photovoltaic was estimated to be about 89% of total installed PV in the US. 1996, the percentage decreased to 65% while in 2006 the statistics of ABS research indicated and rapid turnover in the usage of the photovoltaic in the grid-connected was estimated about 88%. These percentages represent the volume of the distributed generation and centralized generation however; this is not the case for most of the developed countries with poor transmission capabilities as the electricity needs to be distributed to remote location that the distribution networks are incapable of performing this task. Solar photovoltaic is relatively low in these countries nevertheless, with the fast initial economic growth, consumer take-up together along with the technological associations and government's commitments, these countries are holding promising marketing niches for this technology (ABS Energy Research, 2006). Although the cost of photovoltaic panels has been significantly reduced during the last few years, stand alone PV systems have not been able to compete up to date with conventional generating Plants Source (El-Sayed, 2005). In the past three years, annual growth considering large-scale photovoltaic plants was on average almost 100% annually (El-Sayed, 2005; Find Solar, n.d.).

The efficiency of the device is a function of the intrinsic band gap of the silicon, its absorption of the wavelengths of light present in sunlight in the p-doped layer and the transmission of the same light through the n-doped layer. The electrical conductivity of both layers also contributes to the efficiency. Current silicon solar cell technology utilizes single-crystal, amorphous and polycrystalline forms of silicon. Photocells have also been constructed from GaAs, CdTe, and copper-indium-diselenide.

Quantum dot Solar Cells

Since the development of solar cells few decades ago, the conducted research has been focusing

on how to improve the operational efficiency of the solar cells (Bukowski & Simmons, 2002). The limitations in solar conversion efficiency exhibited by the poor match between the band gap of silicon and the sunlight spectrum, can be overcome, in principle, by adjusting the absorption of the underlying semiconducting material (Nozik, 2001). By physically constructing the photodiodes to have nano-scale dimensions, additional absorptions states are introduced into the original semiconductor band gap. In particular, these allow increased absorption at longer wavelengths, where the intrinsic material is normally transparent. The efficiency for intrinsic material photocells is limited to around 33%. Projections and early measurements indicate that quantum dot based solar cells are capable of 66% efficiency.

The quantum dots are specific types of semiconductor that their molecules are designed in very small size and shape, nano-scale size. The main advantage of the quantum dots material is their responsiveness to the different wavelengths of the solar spectrum compared to the traditional semiconducting materials characterized by discrete energy levels. When a photon strikes a solar cell made of this special new material, unlike the traditional semiconductor cells, most of the energy can be useful in exciting multiple electrons resulting in an increase of the current generation which could result in better and more efficient solar cells (Nozik, 2001; Evident Tech, n.d.). The present cost (Generation I) based on single crystal Si is about \$3.50/peak watt, yielding an energy cost of about \$0.30 to 0.35 /kWhr (Nozik, 2001). The grand future challenge for photovoltaic's is to discover and develop PV systems that exhibit combinations of efficiency and capital cost per unit area that result in a cost of about \$0.20/peak watt corresponding to delivered electrical energy of a few cents/kWhr. A cost level of \$0.20/peak watt would make PV very attractive and lead to widespread application. Such a cost goal requires PV at \$100/m² together with a conversion efficiency of about 45% or PV at \$2/m² and an

efficiency of 15% such combinations of cost and efficiency require truly disruptive technologies that do not exist at the present time. However, the attainment of these goals does not conflict with nor violate any fundamental scientific principles and is theoretically feasible (Nozik, 2003).

Solar Ponds

The solar pond systems are based on a passive absorption of thermal technology-- they rely on a natural or designed lake which holds water with salt dissolved in it. Typically, the pond consists of three distinct layers of water:

- The top layer, which has a relatively low salt content and is optically transparent allowing the sunlight to penetrate to the deeper layers.
- An intermediate insulating layer with a slightly increased salt content, which establishes a density gradient that prevents heat exchange by natural convection.
- The bottom layer, which has a high salt content giving it maximum density as high thermal capacity.

The working principle of solar ponds^{5,6} is based on the capture of solar radiation heat in a salt solution. Sunlight passes through the 3 layers and is absorbed in a black absorbing surface at the bottom of the pond. When solar radiation strikes the pond, most of it is absorbed by the surface at the bottom of the pond. The temperature of the dense salt layer therefore increases. If the pond contained no salt, the bottom layer would be less dense than the top layer as the heated water expands. The less dense layer would then rise up and the layers would mix. But the salt density difference keeps the 'layers' of the solar pond separate. The denser salt water at the bottom prevents the heat being transferred to the top layer of fresh water by natural convection; the heat thus absorbed then

warms to bottom layer leading to an increase in water temperature to about 90-100° C.

In order to extract the energy stored in the bottom layer, hot water is removed continuously from the bottom, passed through a heat exchanger and then returned to the bottom. To generate electricity, heat stored in hot water is piped to an evaporator. Liquid Freon® (or other such refrigerant) in the evaporator is heated and converted into gas. The pressure generated by the gas spins a turbine and electricity is produced by the generator. Freon® gas is then cooled and recycled and used again. This system has an additional advantage in that the thermal mass of the pond can be used to store energy for use at night or on cloudy days.

This technology offers several sets of advantages in terms of producing clean power without the need of burning any fossil fuel by running the hot water through a heat exchanger to extract the heat and let a refrigerant to absorb it to run a turbine to generate electricity. The disadvantage is that there are not that many natural lakes with salt solution making the design and creation of this pond more costly (adding resources of salt). The feasibility of this technology has demonstrated low-cost operations small electricity generation application. The largest operating solar pond for electricity generation was the Bet Ha-Arava pond built in Israel and operated up until 1988. It had an area of 210,000 m² and gave an electrical output of 5 MW⁷ (Wikipedia, 2010). This technology is ideal to be used in the sea water desalination plant with total independency on fossil fuel (Straatman & Van Sark, 2007).

Notable drawbacks to this technology are their significant water consumption due to evaporation and the associated cooling.

RESULTS

Data collection was done by literature research and expert survey. We started with the literature research on the technologies under. This was very

helpful for us to understand how each technology works, and their advantages and disadvantages..

A Bibliometric analysis was also done along with the literature research to evaluate the relative maturity as indicated by publications, for each technology. The relative maturity data from the Bibliometrics was used in the decision making process which will be explained later in this section. We surveyed two sets of experts. We surveyed three local experts in SA on the criteria and sub-criteria. Local experts were chosen as they were in the best position to act as decision makers. We surveyed two international experts on solar technology to compare and evaluate the technologies for each criteria and sub-criteria.

A survey document was developed for the local experts in SA to complete. This survey was a pair-wise comparison of the characteristics of efficiency, technology maturity, environmental impact, life time and cost. The survey also included the pair-wise comparison of the sub-criteria under each criterion. The experts provided numerical values for the importance of each characteristic when compared with each of the other four characteristics. The values from each expert were then entered into a pairwise comparison software (PCM). The software calculated the individual's weights for each characteristic as well as the combined weights for all experts. A second survey document was developed for the international solar technology experts. This survey was a pair-wise comparison of the four technologies for each sub-criteria and criteria environmental impact and lifetime. The same process was followed by feeding the numbers into the PCM software resulting in the individual's weight for each technology under each sub-criterion and criteria as well as the combined weights for all experts. The combined weights computed for each characteristic (Criteria level) and the combined weights computed for each sub-criterion (Sub-criteria level) were combined with weights obtained for each technology each sub-criterion and criteria by multiplying them all together to get the final normalized value for each

technology with respect to each characteristic and then summed together to determine the overall ranking of the technologies based on these combined weights. The results of these calculations are given in the next section.

The process flow of the project is shown in the figure below. The relative weights of criteria, sub-criteria and technologies as seen in the PCM software is shown in Appendix. The inconsistency value obtained on each PCM calculation is shown in Appendix. The inconsistency value ranges from 0 to 0.114, which is in the acceptable limit.

Below are the results of PCM for all five major criteria's. Cost (0.29) is the highest ranking characteristic, followed by life time (0.26), environment impact (0.19), efficiency (0.16) and tech maturity (0.09).

Analyzing the results of sub-criteria, commercialization (0.58) is given more weight than bibliometrics (0.42) under Technology maturity. Under efficiency, Output factor (0.57) is given more weight than Conversion efficiency (0.43). Installation cost (0.35) is the highest ranked sub-criterion under cost followed by Electricity generation cost (0.22).

For the criterion of efficiency, the highest ranked technology is Parabolic Troughs (0.38), followed by Solar Tower (0.34), Photo-Voltaic (0.16) and Quantum Dot (0.11). The PCM results for efficiency are in-line with our research also. CSP technologies (Parabolic Troughs and Solar Towers) are most efficient solar technologies. For Tech maturity, Photo-Voltaic and Parabolic Troughs (0.35) is number one, followed by Solar Towers (0.19) and Quantum Dots (0.10). For environment impact, rankings are Quantum Dots (0.29), Parabolic Troughs (0.26), Photo-Voltaic (0.22) and Solar Towers (0.22). Solar Tower and Parabolic Troughs have highest life time rating of 0.30 followed by Photo-Voltaic (0.25) and Quantum Dots (0.16). All of the technologies are very close in Cost category and get the equal pie. Photo-Voltaic and Solar Tower are 0.26 whereas

Figure 2. Research flow

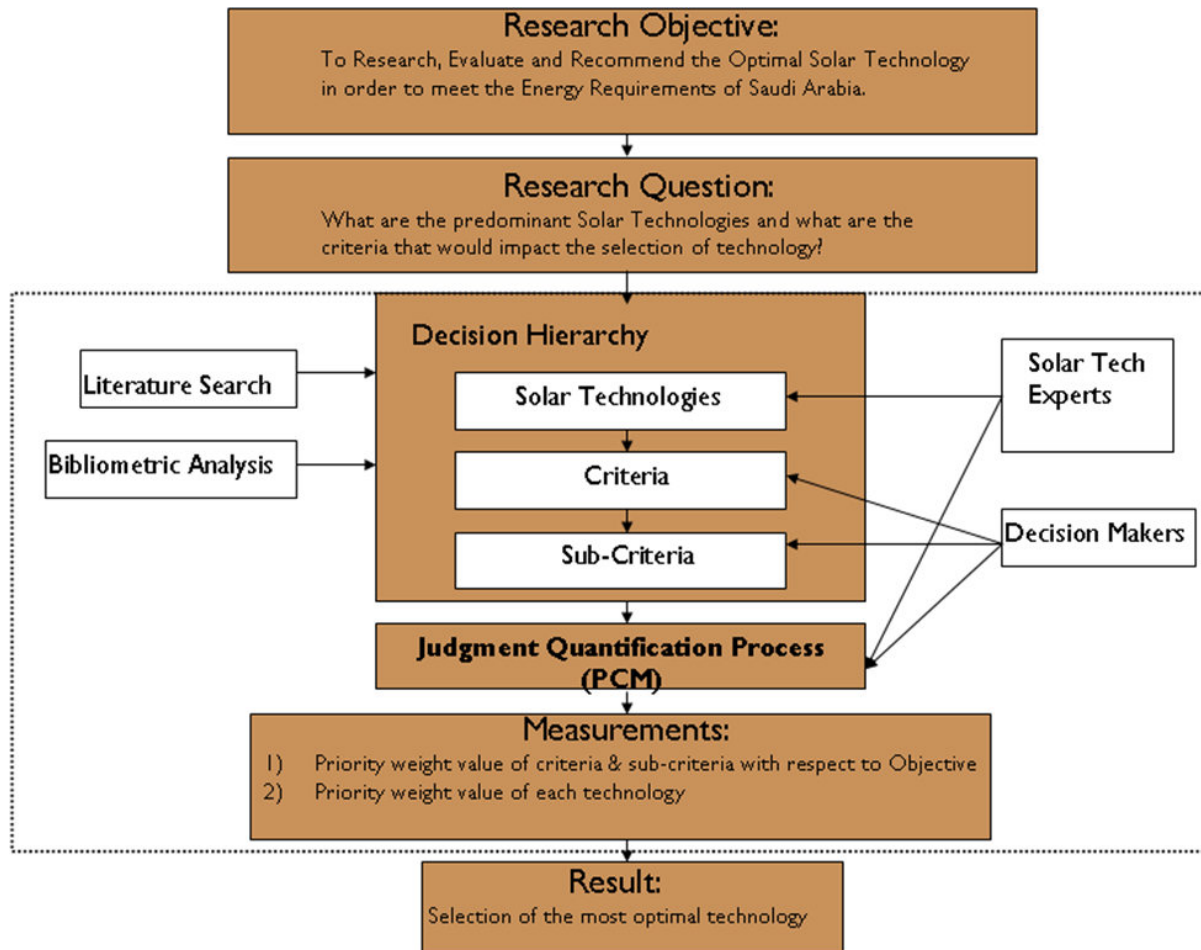


Figure 3. Criteria weights

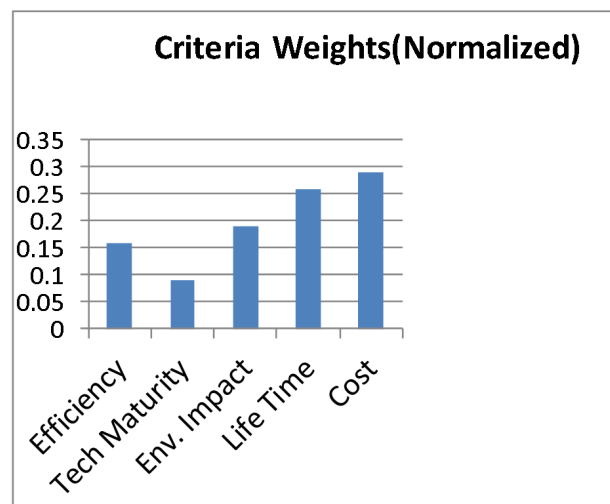


Figure 4. Sub criteria weights

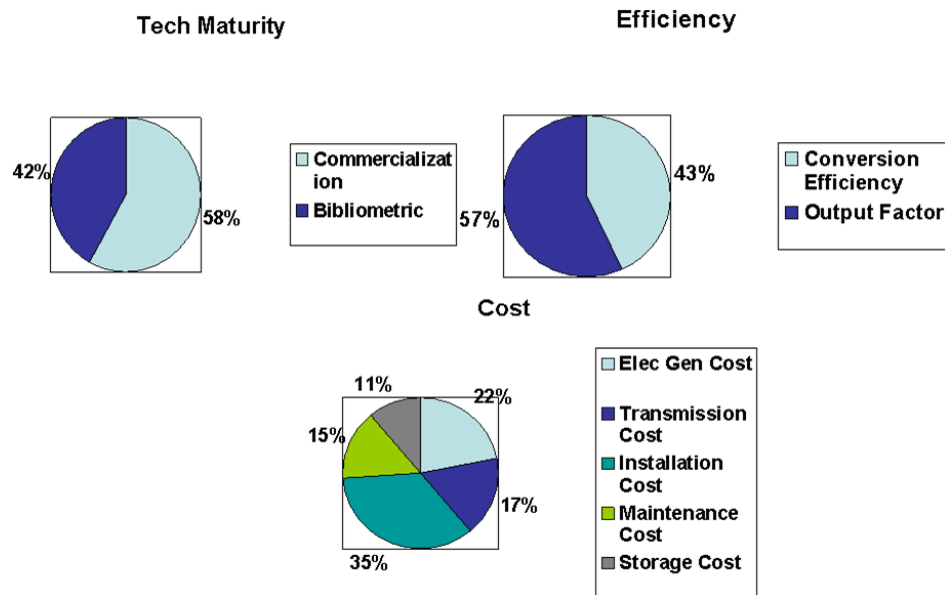


Figure 5. Sub technology scores across criteria

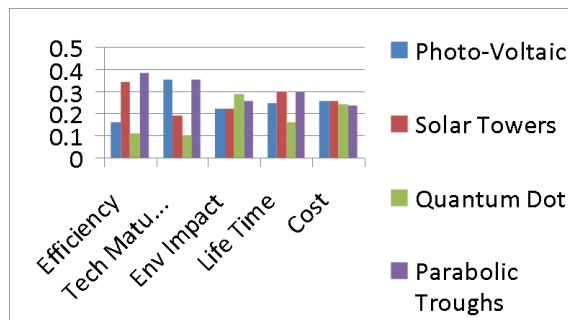
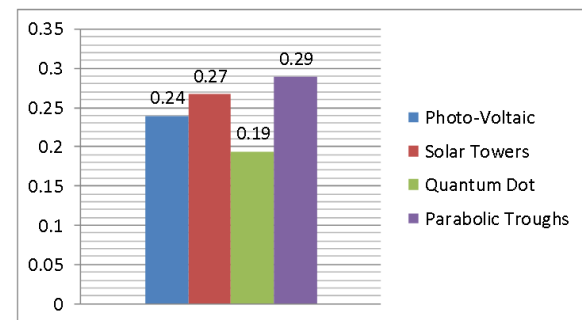


Figure 6. Final results



Quantum Dot and Parabolic Troughs are 0.24 in this category.

On combining the total score for each criterion for all technologies, Parabolic Troughs emerged as a winner with a score of (0.289), followed by Solar Tower (0.267), Photo-Voltaic (0.239) and Quantum Dot (0.193). We compared the results with a recently published report from SEPA (Solar Electric Power Association). The results of the SEPA report show that CSP's (Parabolic troughs and solar towers) are very efficient in electricity generation (5042 MW) when compared to Photo-Voltaic (2379.4 MW). This

result supports our conclusion that parabolic troughs and solar towers are the top 2 optimal technologies.

SENSITIVITY ANALYSIS

Decision makers for our model gave maximum weighting to cost and minimum to maturity. Based on these values, Parabolic Troughs and Solar Tower are first and second, followed by Photo-Voltaic and Quantum Dots. The table below shows how the results are varying if we allocate different

Table 3. Sensitivity analysis

Scenarios	Efficiency	Maturity	Environmental Impact	Life	Cost	Results Order	Difference between top 1 & 2
Actual	0.16	0.09	0.19	0.26	0.29	PT-ST-PV-QD	0.022
Swap the weights between efficiency & cost	0.29	0.09	0.19	0.26	0.16	PT-ST-PV-QD	0.030
Swap the weight between maturity & cost	0.16	0.29	0.19	0.26	0.09	PT-PV-ST-QD	0.054
Swap the weight between maturity & cost (and remove Bibliometric)	0.16	0.29	0.19	0.26	0.09	PV-PT-ST-QD	0.004
Remove bibliometrics	0.16	0.09	0.19	0.26	0.29	PT-ST-PV-QD	0.007
Same weight	0.2	0.2	0.2	0.2	0.2	PT-ST-PV-QD	0.044

weights to the criteria. In most of the cases, Parabolic Troughs is leading. One interesting thing to note is that Photo-Voltaic became the winner if we swap the weights between tech maturity and cost and remove Bibliometric sub criteria from our decision model. We can conclude that if we give more importance to technology maturity, then Photo-Voltaic is the winner. This is in-line with our literature research also.

RECOMMENDATIONS AND CONCLUSION

The key objective of this research study was to select the optimal technology for sustainable electrical power generation in Saudi Arabia. Our *modus operandi* to achieve the objective was researching the available Literature, collecting inputs from the experts and processing them into a measurable result. We conclude this study by stating that the solar electrical power generation through the use of Parabolic Troughs is the optimal technology to achieve the energy sustainability in the region. Our consultation with a smaller number of experts was due to the challenge we had in accessing remotely

located resources within a short time span. It would be interesting to see how the results could have changed, with the participation of more experts and local resources in this technology evaluation study. Our recommendation in this regard for the Saudi Arabian Government or a private investor is to develop our model by the inclusion of more experts in the evaluation.

Another factor to keep in mind is the specific geographic location of where the technology is going to be implemented within Saudi Arabia. The reasons to emphasize location are the solar flux level, the cost of acquiring the land, the reliability and high cost of transmission networks, and the increased local demand associated with high density population centers.

Implementing the right solar technology in Saudi Arabia will not only potentially address the future electrical power generation needs of the local population there, but it may also open up new business opportunities for the country to become a strategic electric power producer capable of supplying not only the Saudi Arabia (SA) power needs but also those of the Middle East and the neighboring countries in Europe. Additionally, even in the short term, generation of electrical

power through sun light, will enable more of SA's petroleum resources to be exported, further augmenting the economy. In order to explore these business opportunities, more research is required as the technology for solar power generation evolves in order to validate and declare that in future, SA indeed can become a major producer of solar power in the world.

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KEY TERMS AND DEFINITIONS

Alternatives: These are the technologies being evaluated – fourth and lowest level in the hierarchy.

Analytic Hierarchy Process: A hierarchical decision process enabling to analyze the problem in hierarchies and calculate contributions of elements at one level to the level above.

Bibliometric Analysis: Use of publication trends to identify technology trends.

Criteria: These are the factors impacting the mission – second level in the hierarchy.

Inconsistency: A metric calculating the variance in the weights calculated when the orientation of the elements in the matrix which is obtained through pairwise comparisons is changed. It indicates how consistent a decision maker is.

Mission: Overall objective of the decision model – top of the hierarchy.

Pairwise Comparison Method: A matrix based method enabling to compare a pair of alternatives at a time and thus calculating the assigned weights based on the comparisons.

Relative Weight: The combined impact/contribution level of an element on a level on all the elements at a higher level.

Sub Criteria: These are the sub factors under the factors – third level in the hierarchy.

ENDNOTES

¹ “Status Report on Solar Thermal Power Plants”, Pilkington Solar International: 1996. Report ISBN 3-9804901-0-6.

² “Introduction to Parabolic troughs” can be found at www.abengoasolar.com/sites/solar/en/technologies/concentrated_solar_power/parabolic_trough/index.htm

³ “Current and Future economics of parabolic trough technology”, Henr Price, Mark Mehos, Chuck Kutscher and Nate Blair - National Renewable energy laboratory Golden Colorado 80401.

⁴ “Towering achievement”, Sanford, Leonard, Modern Power Systems; Aug2009, Vol. 29 Issue 8, p18-21, 3p

⁵ http://mhathwar.tripod.com/thesis/solar/solar_ponds.html

⁶ Heat extraction from a salinity-gradient solar pond using in pond heat exchanger, M.R. Jaefarzadeh, Applied Thermal Engineering, Volume 26, Issue 16, November 2006, Pages 1858-1865

⁷ “Solar Energy in Israel” Professor David Faiman, Ben-Gurion National Solar Energy Center, Jacob Blaustein Institute for Desert Research, Israel Ministry of Foreign Affairs, “spotlight on Israel” 26 Nov 2002

APPENDIX

MATURITY LEVEL OF EACH TECHNOLOGY

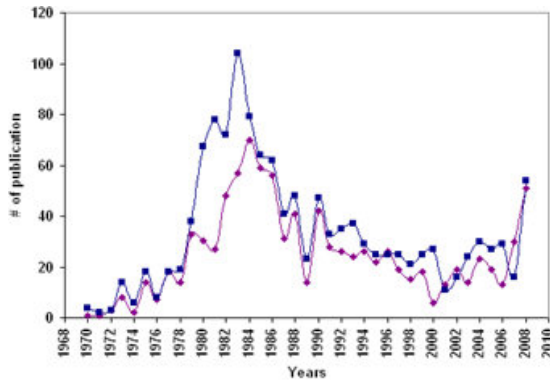
It is difficult to forecast the trend of any given technology in this hyper velocity industrial world as different aspects of it are evolving and get developed at a higher rate every day and other. Daim et al. (2006) suggest using Bibliometric analysis as a tool to measure how mature the technology is. Bibliometric is defined in his study as the measurement of texts and information and it can shed some light on the past of certain technology and understand the pattern of how the technology is receiving attentions of writers and scientist as a measure of how important a certain technology has become and study the growth rate of it.

Databases are widely used in this study with different keywords for the search, matching the content of the publications with the keywords used that best describe the technology. In this study, Business Source Premier was the primary used database to extract patterns for the development of each technology while Compendex (secondary database) was used to verify those results from Business Source Premier. Figure 7 shows the relationship of each filtered technologies and their result and they represent the Bibliometric analysis for each selected technology and their trends. The above results from the graphs have been normalized to extract a value of the maturity rate of each technology. The following table shows the maturity rate for each selected technology. The values extracted from the charts have been normalized relatively to each other to determine a rate of maturity; the following table shows the normalized value of the maturity rate:

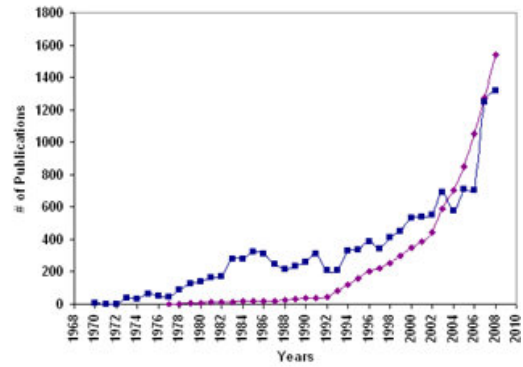
Table 4. Maturity analysis

Technology	Total publication	Average	Rate
Ave of PA	18071	2258.875	10
Ave of QD	230	57.5	0.25
Ave of SP	6490	1622.5	1.4
Ave of PV	10375	1296.875	6.8
Ave of ST	9783	1016.45	4.5

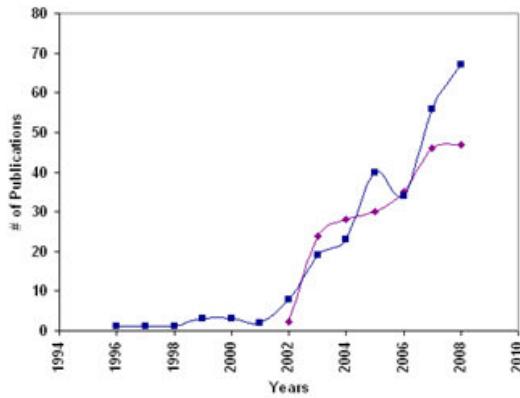
Figure 7. Bibliometric Analysis



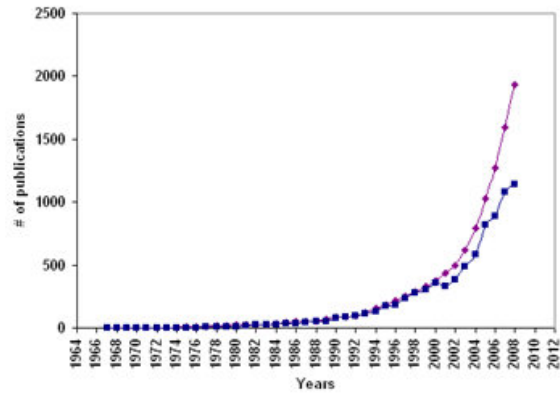
[a] Solar Ponds



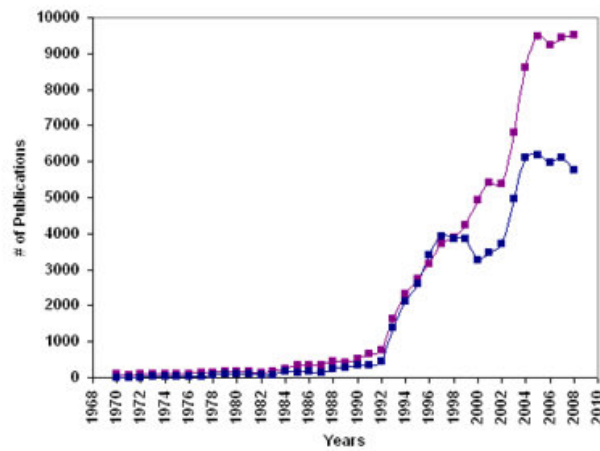
[b] Photovoltaic



[c] Quantum Dots



[d] Solar Towers



[e] Parabolic Troughs

RELATIVE WEIGHTS FROM PCM SOFTWARE

Figure 8. Relative weights for criteria

Users	1	2	3	4	5	Inc'n
Mail 1	0.18	0.09	0.12	0.25	0.37	0.015
Mail 2	0.16	0.11	0.17	0.24	0.32	0.011
3rd Person	0.16	0.08	0.28	0.30	0.17	0.020
Mean	0.16	0.09	0.19	0.26	0.29	0.063
Min	0.16	0.08	0.12	0.24	0.17	

Item Name Definition

- Efficiency
- Technology Maturity
- Environmental Impact
- Lifetime
- Cost

F1 = Help, F2 = Save item names.

ESC=Exit, F1=Help, F2=Name/Items, F3=Save, F4=Display, ←=Pairs.

Figure 9. Relative weights for sub-categories of cost

Users	1	2	3	4	5	Inc'n
Mail 1	0.21	0.17	0.39	0.13	0.10	0.001
Mail 2	0.18	0.18	0.41	0.12	0.11	0.015
3rd Person	0.28	0.16	0.25	0.20	0.12	0.004
Mean	0.22	0.17	0.35	0.15	0.11	0.050
Min	0.18	0.16	0.25	0.12	0.10	

Item Name Definition

- Electricity Generation Cost
- Transmission Cost
- Installation Cost
- Maintenance Cost
- Storage Cost

F1 = Help, F2 = Save item names.

ESC=Exit, F1=Help, F2=Name/Items, F3=Save, F4=Display, ←=Pairs.

Figure 10. Relative weights of technologies on conversion efficiency

Users	1	2	3	4	Inc'n
C SHEBLE	0.20	0.30	0.20	0.30	0.000
NASIR SHEIK	0.17	0.35	0.04	0.43	0.004
Mean	0.18	0.33	0.12	0.37	0.076
Min	0.17	0.30	0.04	0.30	
Max	0.20	0.35	0.20	0.43	

Item Name Definition

- Photo-Voltaic
- Solar Towers
- Quantum Dot
- Parabolic Troughs

F1 = Help, F2 = Save item names.

ESC=Exit, F1=Help, F2=Name/Items, F3=Save, F4=Display, ←=Pairs.

Figure 11. Relative weights of technologies on output factor

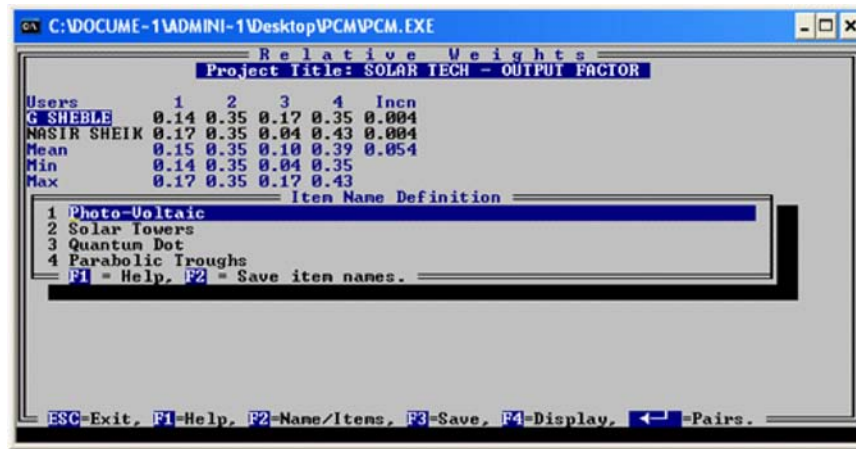


Figure 12. Relative weights of technologies on commercialization

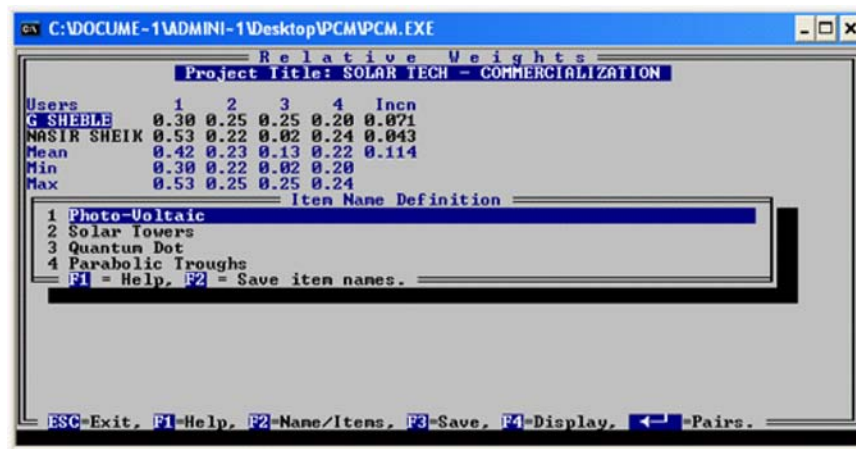
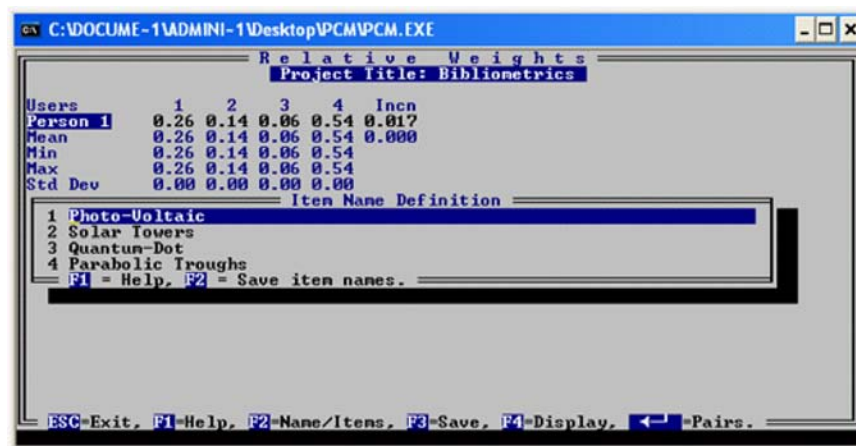


Figure 13. Relative weights of technologies on bibliometrics



Technology Selection for Solar Power Generation in the Middle East

Figure 14. Relative weights of technologies on electricity generation cost

Project Title: SOLAR TECH - ELEC GENERATION COST

Users	1	2	3	4	Incn
G SHEBLE	0.26	0.36	0.16	0.22	0.004
NASIR SHEIK	0.25	0.27	0.25	0.23	0.036
Mean	0.26	0.32	0.20	0.22	0.046
Min	0.25	0.27	0.16	0.22	
Max	0.26	0.36	0.25	0.23	

Item Name Definition

- 1 Photo-Voltaic
- 2 Solar Towers
- 3 Quantum Dot
- 4 Parabolic Troughs

F1 = Help, F2 = Save item names.

ESC=Exit, F1=Help, F2=Name/Items, F3=Save, F4=Display, ←=Pairs.

Figure 15. Relative weights of technologies on transmission cost

Project Title: SOLAR TECH - TRANSMISSION COST

Users	1	2	3	4	Incn
G SHEBLE	0.10	0.40	0.10	0.40	0.000
NASIR SHEIK	0.25	0.25	0.25	0.25	0.000
Mean	0.17	0.32	0.17	0.32	0.106
Min	0.10	0.25	0.10	0.25	
Max	0.25	0.40	0.25	0.40	

Item Name Definition

- 1 Photo-Voltaic
- 2 Solar Towers
- 3 Quantum Dot
- 4 Parabolic Troughs

F1 = Help, F2 = Save item names.

ESC=Exit, F1=Help, F2=Name/Items, F3=Save, F4=Display, ←=Pairs.

Figure 16. Relative weights of technologies on installation cost

Project Title: SOLAR TECH - INSTALLATION COST

Users	1	2	3	4	Incn
G SHEBLE	0.25	0.25	0.25	0.25	0.000
NASIR SHEIK	0.30	0.20	0.30	0.20	0.000
Mean	0.28	0.22	0.28	0.22	0.035
Min	0.25	0.20	0.25	0.20	
Max	0.30	0.25	0.30	0.25	

Item Name Definition

- 1 Photo-Voltaic
- 2 Solar Towers
- 3 Quantum Dot
- 4 Parabolic Troughs

F1 = Help, F2 = Save item names.

ESC=Exit, F1=Help, F2=Name/Items, F3=Save, F4=Display, ←=Pairs.

Figure 17. Relative weights of technologies on maintenance cost

Relative Weights					
Project Title: Solar_maintenanceCost					
Users	1	2	3	4	Incn
Nasir	0.30	0.20	0.30	0.20	0.000
Gerald	0.00	0.00	0.00	0.00	0.000
Mean	0.30	0.20	0.30	0.20	0.000
Min	0.30	0.20	0.30	0.20	
Max	0.30	0.20	0.30	0.20	

Item Name Definition

- 1 PU
- 2 Solar Tower
- 3 QD
- 4 Parabolic Troughs

F1 = Help, F2 = Save item names.

ESC=Exit, F1=Help, F2=Name/Items, F3=Save, F4=Display, ←=Pairs.

Figure 18. Relative weights of technologies on storage cost: 1) Photo-Voltaic, 2) Solar Tower, 3) Quantum-Dot, 4) Parabolic Troughs

Relative Weights					
Project Title: Solar_StorageCost					
Users	1	2	3	4	Incn
Nasir	0.25	0.25	0.25	0.25	0.000
Gerald	0.25	0.25	0.25	0.25	0.000
Mean	0.25	0.25	0.25	0.25	0.000
Min	0.25	0.25	0.25	0.25	
Max	0.25	0.25	0.25	0.25	
Std Dev	0.00	0.00	0.00	0.00	

ESC=Exit, F1=Help, F2=Name/Items, F3=Save, F4=Display, ←=Pairs.

Figure 19. Relative weights of technologies on environmental impact: 1) Photo-Voltaic, 2) Solar Tower, 3) Quantum-Dot, 4) Parabolic Troughs

Relative Weights					
Project Title: Solar_EnvironmentallImpact					
Users	1	2	3	4	Incn
Nasir	0.20	0.20	0.33	0.27	0.004
Gerald	0.25	0.25	0.25	0.25	0.000
Mean	0.22	0.22	0.29	0.26	0.039
Min	0.20	0.20	0.25	0.25	
Max	0.25	0.25	0.33	0.27	
Std Dev	0.04	0.04	0.06	0.01	

ESC=Exit, F1=Help, F2=Name/Items, F3=Save, F4=Display, ←=Pairs.

Technology Selection for Solar Power Generation in the Middle East

Figure 20. Relative weights of technologies on life time: 1) Photo-Voltaic 2) Solar Tower 3) Quantum-Dot 4) Parabolic Troughs

The screenshot shows a window titled "Relative Weights" with the project title "Solar LifeTime". It displays a table of weights for four technologies (1, 2, 3, 4) across five criteria (Users, Nasir, Gerald, Mean, Min, Max, Std Dev). The bottom of the window shows keyboard shortcuts: ESC=Exit, F1=Help, F2=Name/Items, F3=Save, F4=Display, and a left arrow key for Pairs.

	1	2	3	4	Incn
Users	0.29	0.29	0.13	0.29	0.000
Nasir	0.20	0.30	0.20	0.30	0.000
Gerald	0.25	0.30	0.16	0.30	0.042
Mean	0.20	0.29	0.13	0.29	
Min	0.29	0.30	0.20	0.30	
Std Dev	0.06	0.01	0.05	0.01	

Figure 21. PCM output

Criteria					No of Persons	Inconsistency
Efficiency	Tech Maturity	Env Impact	Lifetime	Cost	3	0.063
0.16	0.09	0.19	0.26	0.29		
Cost					No of Persons	Inconsistency
Elec Gen	Transmission	Installation	Maintenance	Storage	3	0.05
0.22	0.17	0.35	0.15	0.11		
Solar Tech - Conversion Efficiency					No of Persons	Inconsistency
PV	ST	QD	PT	2	0.076	
0.18	0.33	0.12	0.37			
Solar Tech - Output Factor					No of Persons	Inconsistency
PV	ST	QD	PT	2	0.054	
0.15	0.35	0.1	0.39			
Solar Tech - Commercialization					No of Persons	Inconsistency
PV	ST	QD	PT	2	0.114	
0.42	0.23	0.13	0.22			
Solar Tech - Bibliometrics					No of Persons	Inconsistency
PV	ST	QD	PT	1	0.017	
0.26	0.14	0.06	0.54			
Solar Tech - Electricity Generation Cost					No of Persons	Inconsistency
PV	ST	QD	PT	2	0.046	
0.26	0.32	0.2	0.22			
Solar Tech - Transmission Cost					No of Persons	Inconsistency
PV	ST	QD	PT	2	0.106	
0.17	0.32	0.17	0.32			
Solar Tech - Installation Cost					No of Persons	Inconsistency
PV	ST	QD	PT	2	0.035	
0.28	0.22	0.28	0.22			
Solar Tech - Maintenance Cost					No of Persons	Inconsistency
PV	ST	QD	PT	2	0	
0.3	0.2	0.3	0.2			
Solar Tech - Storage Cost					No of Persons	Inconsistency
PV	ST	QD	PT	2	0	
0.25	0.25	0.25	0.25			
Solar Tech - Environmental Impact					No of Persons	Inconsistency
PV	ST	QD	PT	2	0.039	
0.22	0.22	0.29	0.26			
Solar Tech - Lifetime					No of Persons	Inconsistency
PV	ST	QD	PT	2	0.042	
0.25	0.3	0.16	0.3			

Chapter 19

Solar Energy Education and Training Programs in the USA: An Academic Perspective

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ABSTRACT

In the past, solar energy education was limited to scientists and engineers who could develop new technologies and conduct research. Later on, a need was recognized to educate those who design and construct buildings, because solar energy applications were well developed for such applications. At present, numerous solar energy applications have been developed. Solar energy is currently used for heating and cooling of buildings, production of electricity for stationary and mobile applications, solar lighting systems, crop drying, water treatment, and environmental cleanup. Given the expanding use of solar energy, there is a need to educate society about solar energy. Thus, solar energy education and training programs should be developed at different educational levels to fulfill this need. Such programs need to recognize the environmental value of solar energy and the life cycle advantages of solar energy systems. This manuscript provides an overview of the status of solar energy education and training in the United States. Though the focus of this chapter is on the solar energy education and training programs provided by the academic institutions in the USA, a short description of non-academic programs is also provided.

INTRODUCTION

A trademark of the economic growth in the United States is an ever-increasing demand for energy. Traditionally, this demand has been primarily fulfilled through the use of fossil fuels. However, the

fossil fuels are non-renewable, that is, they draw on finite resources that will eventually dwindle, becoming too expensive or too environmentally damaging to retrieve. Thus, the quest for a clean, safe, and efficient environment has led to the search for alternative energy resources.

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The energy resources such as solar, wind, geothermal, hydropower, and biomass have been identified as renewable energy. The climate change concerns coupled with high oil prices are driving increasing renewable energy legislation, incentives, and commercialization (Petrovic, Munukutla, & Robertson, 2007; European Renewable Energy Council, 2007; Al Kalaani, 2005; Al Kalaani & Rosentrator, 2007). The key benefits of renewable energy technologies include:

1. Utilize locally available resources
2. Enhance energy security by diversifying the energy portfolio, improving price stability in times of rising fossil fuel costs, and reducing risks associated with future energy cost uncertainties.
3. Match well to a variety of grid, off-grid, remote, and distributed applications.
4. Are environmentally beneficial, lacking the nitrogen and sulfur oxides that are harmful to human, animals, and plants, and carbon dioxide and methane emissions which contribute to climate change.

Solar energy is one form of renewable energy. It is clean, sustainable, and does not produce carbon dioxide or other harmful gases. The applications of solar energy include:

- Generate electricity by heating air to rotate turbines in a Solar updraft tower
- Generate electricity in geosynchronous orbit using solar power satellites
- Generate electricity using photovoltaic solar cells
- Generate electricity using concentrated solar power
- Generate hydrogen using photoelectrochemical cells
- Heat and cool air through use of solar chimneys

- Heat buildings, directly, through passive solar building design
- Heat food using solar ovens
- Heat water or air for hot water and space heating using solar-thermal panels
- Solar air conditioning

However, despite the global awareness and concerns regarding environmental degradation, the present public policies in many countries do not favor the use of solar energy over conventional fuels (Goswami, 2001). Using conventional financial tools, many solar energy applications do not appear cost effective. In order to develop effective public policies that recognize the environmental value of solar energy and the financial tools that demonstrate the life cycle advantage of solar energy systems, it is important to properly educate public policy makers, financial professionals, and the general public. In the United States, the solar energy education is available at the following competency levels:

- College Education (Undergraduate and Graduate)
- Technical Education (Certificate and Associate Degree)
- Schools (K – 12)
- Workshops and Seminars for general public

This chapter focuses on solar energy education in the United States (U.S.A.). The academic perspective is emphasized in the manuscript.

UNDERGRADUATE AND GRADUATE EDUCATION

Solar energy education at the college/university level is perhaps the most developed. Well developed curricula at the undergraduate and graduate levels are available at many colleges and

universities in the USA. Brief descriptions of the graduate and undergraduate solar energy education programs available at the selected universities and colleges in the USA are presented below.

Description of Courses and Programs

The Arizona State University (ASU) offers a Solar Energy Engineering & Commercialization graduate program. This program provides interdisciplinary graduate education in solar energy to engineering, science or technology students. The program prepares graduates for careers in industry and government that involve solar energy. Students in this program are required to choose courses from both technical and nontechnical study areas spanning a number of academic disciplines. The degree program is meant to be completed in 12 months for full-time graduate students.

The University of Illinois at Chicago offers a Master of Energy Engineering program. This program prepares graduates to work in all aspects of the energy industry. They may pursue careers in energy generation and distribution or in energy utilization. The Master of Energy Engineering program focuses on the dual considerations of energy efficiency and environmental responsibility and serves the professional workforce needs of several major industrial organizations in northern Illinois and the surrounding region. To be considered for admission in this graduate program, a baccalaureate degree or its equivalent in engineering, mathematics, computer science, or a natural science from an accredited college or university is required.

Oregon Institute of Technology (Oregon Tech) with campuses located in Klamath Falls and Portland, introduced the first Bachelor of Science in Renewable Energy Systems in USA (now known as Renewable Energy Engineering). Oregon Tech's renewable energy program establishes the engineering principles needed by the program graduates to develop, implement, and utilize

sustainable energy technologies. Upper-division renewable-energy specific courses include photovoltaics, energy management and auditing, wind power, biofuels, renewable-energy transportation systems, green building and fuel cells. The Renewable Energy curriculum of Oregon Institute of Technology prepares graduates for engineering careers in the energy sector in general, and the renewable energy in particular. Graduates of the program are prepared for graduate study or for employment as field engineers, energy auditors, renewable energy system integrators for homes and businesses, manufacturing engineers for component and subsystem manufacturers, designers for components and subsystems, local and state government renewable-energy inspectors, planners and other positions in the energy discipline.

Other worth mentioning graduate and undergraduate programs in solar energy include:

The Stanford University Department of Energy Resources Engineering offers a graduate degree program leading to a Master's or a Ph.D degree in Energy Resources Engineering. The objective of the M.S. degree is to prepare the students for professional careers or for doctoral studies in energy-related disciplines. The course sequence alternatives for the M.S. degree include geothermal energy, low carbon energy, oil and gas, and modeling of natural resources.

University of Massachusetts Lowell offers professional education in renewable (solar) engineering at the master's degree level to prepare students for careers in energy-related disciplines. The required courses include Fundamentals of Solar Utilization and Solar Systems Engineering. In addition, the University of Massachusetts Lowell offers a Ph.D program in energy engineering. The two areas of concentration are renewable (solar) energy and nuclear energy. The renewable (solar) energy Ph.D program is administered by the Department of Mechanical Engineering.

The Arizona State University Solar Energy Engineering and Commercialization graduate program focuses on the advanced interdisciplin-

ary education in solar energy. After completing the program, graduates may pursue careers involving solar energy and its utilization. Students select a number of courses from both technical and nontechnical academic tracks. The graduate program also includes an applied research project focusing on solar energy and its commercialization. The courses and the research project allow graduate students to develop a comprehensive understanding of solar energy technologies along with the business/nontechnical aspects needed for development and commercialization.

John Brown University, in Arkansas, provides a bachelors of science program in renewable energy. The design concentration of this undergraduate major trains students for renewable energy systems design and integration. The management concentration allows students to combine business courses with renewable energy. The international development concentration combines intercultural studies with the courses in renewable energy.

Major energy engineering programs offered at the Pennsylvania State University University Park Campus include B.S. in Energy Engineering; M.S in Energy and Mineral Engineering – Environmental Health and Safety Engineering; M.S. in Energy and Mineral Engineering – Energy Management and Policy; M.S. in Energy and Mineral Engineering – Fuel Science; M.S. in Energy and Mineral Engineering – Mining and Mineral Process Engineering; M.S. in Energy and Mineral Engineering – Petroleum and Natural Gas Engineering; Ph.D. in Energy and Mineral Engineering – Energy Management and Policy; Ph.D. in Energy and Mineral Engineering – Environmental Health and Safety Engineering; Ph.D. in Energy and Mineral Engineering – Fuel Science; Ph.D. in Energy and Mineral Engineering – Mining and Mineral Process Engineering and Ph.D. in Energy and Mineral Engineering – Petroleum and Natural Gas Engineering.

University of Massachusetts Lowell offers energy engineering programs such as Doctor of Engineering in Energy Engineering; Doctor of

Philosophy in Energy Engineering; Master of Science in Energy and Engineering and Masters in Energy Engineering – Nuclear Option.

To illustrate the content of some of the undergraduate solar energy programs offered by the universities and colleges in the United States, descriptions of selected Oregon Tech energy engineering courses are presented below. These descriptions are obtained from the Oregon Institute of Technology Portland website (<http://www.oit.edu/portland/programs>) and they were current at the time this chapter was written (in 2011)

Introduction to Renewable Energy

An Introduction to renewable energy. Topics include photovoltaics, solar thermal systems, green building, fuel-cells, hydrogen, wind power, waste heat, biofuels, wave power, tidal power and hydroelectric. Discussions of components of the course.

Electromechanical Energy Conversion

AC machines, including single phase, split-phase and three-phase (induction and synchronous machines) motors and generators; introduction to power switching devices, speed control and brushless DC motors. DC machines including shunt, series and compound. Control motors. DC machines including shunt, series and compound. Control devices and circuits, including ladder diagrams.

Fuel Cells

Introduction to fuel cell technologies: PEM, PAFC, AFC, SOFC, MCFC and DMFC systems. Fuel cell components and systems; field flow plates, electrolytes, electrode materials, electrode catalysts, on-board reformers. Portable devices, utility-scale power production, transportation systems. Fuel types and fuel storage.

Batteries

This course covers fundamentals of the most important battery types including alkaline, zinc-air, lead-acid, nickel-cadmium, nickel-metal hydride, lithium ion, and lithium polymer. Applications include stationary, transportation, and portable batteries. The lab deals with battery system design, testing, and prototype assembly.

Solar Thermal Energy Systems

Introduction to solar thermal energy systems for residential, commercial and industrial applications. Solar radiation; topics in heat transfer; flat plate and concentrating collectors; non-imaging optics; applications including water heating, building heating, cooling, industrial process heat, distillation, solar thermal power systems.

Photovoltaic Systems

Grid-connected and stand-alone PV systems. Module and array performance analyzed using Sandias IV tracer software. PV system components including batteries, PV modules, charge controllers, maximum power point trackers and inverters will be discussed. Power inverter parameters will be evaluated.

Building Energy Auditing and Management

Principles and applications of energy management in buildings, using auditing to identify opportunities for improving energy efficiency. Analysis of thermal and electrical loading, timing and efficiency of load components. Improving efficiency of thermal and electrical loads, including economic analysis. Application of renewable energy in the analysis of loading and efficiency and effective means of tracking and managing energy use.

Use of Project-Based Instructional Approach for Solar Energy Education

Project-based learning is an instructional approach that focuses on learning by doing projects. According to Yousaf, Mustafa, and Cruz (2010), projects are defined as complex tasks, based on challenging problems, that engage students in design, problem-solving, decision making, or investigative activities resulting in realistic products or presentations. According to Mills (2002), project-based learning is based on self-direction and it has a multi-disciplinary orientation. The other characteristics of project-based learning are as follows:

- Project tasks are closer to professional reality.
- Project work is directed to the application of knowledge.
- Project-based learning is fully supported by the courses taught in the relevant curriculum.
- Management of time and resources by the students is of critical importance in project-based learning.

Several case studies describing the use of project-based learning in the renewable energy curricula/courses are presented in this section of the chapter.

Chen, Goodman, Izadian, and Cooney (2010) describe the hands-on projects they used at Indiana University Purdue University (IUPUI) to teach renewable energy courses. A number of hands-on projects focusing on different topical areas of renewable energy, such as fuel cells, wind energy, and solar energy, were assigned to engineering technology students. The project tasks consisted of literature search, experiment design, hardware acquisition or fabrication, device testing, and analysis of experimental results. The IUPUI engineering technology faculty with

expertise in fuel cells, batteries, solar energy, thermal energy, electric circuit design, and power electronics provided mentoring to the students. The key objective of using the project-based instructional approach was to provide the IUPUI engineering technology students with the technical and non-technical skills needed to meet the workforce challenges posed by a fast growing energy economy. Different solar energy projects were conducted by the IUPUI students. One of the solar energy projects involved designing a solar thermal domestic hot water system with optional radiant heating. The second project consisted of the design of a photovoltaic system to provide electrical energy. Students working on the above mentioned solar energy project first developed system specifications and then designed the solar systems. Through these team-based solar energy systems design projects, students developed valuable multidisciplinary skills to meet the technical challenges associated with the design of renewable energy systems. Additionally, the IUPUI students learned how to work effectively in teams. Through these team-based design projects, the IUPUI engineering technology faculty was able to demonstrate that the hands-on instructional approach was quite effective in introducing students to the practical considerations for solar systems design and implementation.

An interesting design project is described by Weissbach (2005). The project focused on the development of a hybrid (solar and wind) renewable energy system to provide sufficient electric power for a family of four, in a 2000 square-foot, 8-room home in Northwestern Pennsylvania. The project involved electrical engineering technology faculty and students at Penn State Erie – The Behrend College. By working on this renewable energy design project, the students gained a valuable insight into the practical considerations associated with the design and capability of wind turbines and the solar panels.

A design-based alternative energy systems course is described by Somerton and Benard

(2006). Students conducted design projects related to different aspects of alternative energy. The computer software tools such as MATLAB and Excel spread sheets were used to design solar energy, wind energy, wave energy, and geothermal energy systems. In addition, students conducted analysis of a fuel cell system and learned the economics of conversion to alternative energy. The use of design projects to teach alternative energy course provided the students with breadth and some depth. The projects enhanced students' learning and they enjoyed the blending of socio-economic aspects of alternative energy with the technical aspects.

An undergraduate project-based renewable energy course is described by Yildiz and Coogler (2010). The course is designed to allow undergraduate technology students develop and apply on in-depth understanding of renewable energy and bio-renewable products. It is a hands-on interdisciplinary course emphasizing technical, economic, and environmental aspects of renewable energy. Since the Spring 2009 semester, students taking this course have conducted numerous hands-on energy projects. These projects include installation of passive solar air and water heaters, green building design, development of energy harvesting systems from renewable energy sources, and the installation of skylights.

A course focusing on renewable energy conversion systems is described by Belu and Husanu (2011). This course is designed for upper level undergraduate and early graduate students in engineering technology disciplines. It covers the energy conversion principles in the disciplinary areas of solar, wind, photovoltaics, power co-generation, energy storage devices, fuel cells, and hydrogen production. Topics, such as, design of hybrid power systems, grid integration of renewable energy systems, and life cycle assessment of renewable energy sources are also covered in this course. During the second half of this course, the students are required to design a hybrid power system which integrates wind, photovoltaic, and

energy storage systems. Upon completion of this course, students are expected to have developed a good understanding of the renewable energy resources and the energy conversion technologies.

Many educational institutions in the USA are currently developing energy-related courses for their conventional engineering and engineering technology undergraduate programs. One such course development effort is described by Li and Soares (2011). An introductory course in renewable energy is being developed for a four-year electronic engineering technology (EET) program. The topics to be covered in this course include energy generation, energy transportation, energy storage, and energy efficiency. The solar energy part of this course will include both solar thermal and solar photovoltaic systems. Their off-grid and on-grid applications will also be covered in this course. Students will be required to conduct projects such as design of nanocrystalline solar cells, design and development of wind turbines, and creation of a Grätzel cell.

The efforts to create a university-based comprehensive center for energy education are described by Rabiee, Miller, and Stepp (2009). This energy education center will offer both two-year and four-year energy-related degrees. The center will also provide opportunities to conduct energy-related projects. In addition, the planned energy education center will develop energy conferences and K-12 curriculum materials in cooperation with regional school districts.

TECHNICAL EDUCATION AND TRAINING

Technical training and certification is important for proper installation and working of solar energy systems. The solar energy certificate and associate degree programs offered by community colleges, technical institutes, and trade schools are of great help in preparing for a career as a solar energy technician. An individual who is trained as a so-

lar energy technician helps construct and install active solar energy systems which require solar collectors, concentrators, pumps, and fans. A solar energy technician also helps in the installation of passive solar energy systems which rely on the best use of windows and insulation to absorb and reflect solar radiation for heating and cooling. A listing of selected community colleges, technical institutes, and trade schools which offer solar energy certificate and associate degree programs is given below:

- Santa Monica College, California: offers an Associate in Arts Degree in Solar Photovoltaic Installation which provides students with both the hands-on skills and the contextual knowledge needed to work in the burgeoning solar industry. Students who complete this degree program can work as solar installers, installation repair technicians, and solar designers.
- Austin Community College, Texas: offers a renewable energy specialization within an associate of applied science degree in electronics and advanced technologies. The courses taught in this specialization include solar thermal systems, solar photovoltaic systems, solar photovoltaic installations, and energy efficient structures and assessments.
- Sierra College, California: offers Solar Technician Program focusing on photovoltaic system installation and maintenance. The program helps students prepare for careers in photovoltaic companies, electric utilities, and government.
- Redrocks Community College, Colorado: offers associate degrees and certificates in solar photovoltaic and solar thermal systems. These programs prepare students for career positions such as solar installers, home energy auditors, and solar designers.
- Fox Valley Technical College, Wisconsin: offers a photovoltaic installer certificate

program. Students gain hands-on skills in photovoltaic design and installation, blueprint reading, industrial safety, and renewable energy basics.

- Greenfield Community College, Massachusetts: offers a certificate program and an associate degree program in renewable energy. These programs focus on skill development relevant to specific renewable energy technologies.
- Northeast Wisconsin Technical College, Wisconsin: offers a Solar Energy Technology Associate Degree in Applied Science which prepares students to meet the needs of the renewable energy workforce. The program provides a skilled workforce of technicians who are able to design, install, operate, and maintain solar electric and solar thermal systems

Lane Community College, Oregon: offers a two-year renewable energy program that teaches students how to improve the energy efficiency of homes and businesses and to install solar-power and wind-power systems.

Other worth mentioning community and technical colleges which offer solar energy education include Central New Mexico Community College, Pima Community College, Diablo Valley College, Salt Lake Community College, Land Community College, San Juan College, and Bronx Community College.

SCHOOLS/K-12 SOLAR ENERGY PROGRAMS

In the United States, numerous organizations assist K-12/school teachers in assessing the professional development, resources, and curriculum materials needed to provide K-12 students with a comprehensive understanding of solar energy. A listing of such organizations is provided below:

- Florida Solar Energy Center, Florida (<http://www.fsec.ucf.edu/en/>): dedicates substantial effort to the development of educational resources for K-12 teachers. The Center has developed several energy curricula for use by school teachers. The Center also conducts a number of energy related educational events to encourage K-12 students to use their knowledge and creativity for solving energy problems.
- Solar Energy International, Colorado (<http://www.solarenergy.org>): provides educational outreach for K-12 students and educators. Classroom presentations featuring interactive and hands-on solar energy activities and scientific experiments are conducted by the Solar Energy International.
- Northeast Sustainable Energy Association, Massachusetts (<http://www.nesea.org>): offers free workshops to school teachers and youth club leaders to learn about solar energy. The K-12 teachers gain skills to mentor their students in applications of solar energy, math, and physical science.
- Interstate Renewable Energy Council, New York (<http://irecusa.org>): provides valuable resources to school teachers and students to accelerate learning in the topical area of solar energy.
- North Carolina Solar Center, North Carolina (<http://www.ncsc.ncsu.edu>): offers a variety of K-12 programs for schools and numerous professional development opportunities for school teachers. The programs offered include cutting-edge research on the latest technologies in solar energy. The primary goal of these programs is to enhance students' understanding of scientific concepts and solar energy technologies.

Other worth mentioning sources of educational programs for K-12 teachers and students include:

- American Solar Energy Society, Boulder Colorado; <http://www.ases.org>
- National Renewable Energy Laboratory (NREL), Golden, Colorado; <http://www.solarliving.org>

WORKSHOPS AND SEMINARS FOR GENERAL PUBLIC

Numerous organizations throughout the United States offer solar training workshops and seminars focusing on solar energy systems and technologies. Such workshops and seminars include topical areas such as photovoltaics, solar thermal, solar installation, solar sales, and solar system design. Some of the organizations offering solar seminar and workshops are listed below:

- Infinite Solar, Pennsylvania (<http://www.solarschoolpa.com>): provides hands-on renewable energy training workshops and courses to prepare individuals for careers in solar industry. Such courses and workshops cover topical areas such as solar photovoltaic design and installation, solar thermal design and installation, and solar sales.
- Verve Solar Consulting, California (<http://www.vervesolar.com>): offers solar business and career course instruction, curriculum development, and instructor training. Also provides solar business consulting, marketing, and strategic planning.
- Sun Pirate, California (<http://www.sunpirate.com>): provides online training focusing on photovoltaic system design and installation and solar hot water systems. The instructor communication within these online courses is achieved using online message boards, e-mails, and phone.
- Solar Energy International, Colorado (<http://www.solarenergy.org>): provides

hands-on and online workshops and seminars focusing on solar energy systems and technologies.

- Everblue Training Institute (<http://www.everblue.edu>): offers workshops and seminars focusing on typical areas such as solar photovoltaics, solar thermal, solar business, and solar installations.

CONCLUSION

The manuscript provides information regarding numerous resources that are available for solar education and training. As mentioned above, such sources include graduate and undergraduate academic programs, technical education and training programs, seminars and workshops, and K-12 education resources. Many Internet resources are available at varied educational levels to provide information regarding solar energy systems, technologies, and applications. All the above mentioned academic and Internet resources are very helpful in developing a sound awareness of the issues related to solar energy and its applications. However, there are many opportunities for developing academic courses and curriculum materials related to the societal, business, and technical aspects of solar energy.

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KEY TERMS AND DEFINITIONS

Concentrated Solar Power: uses lenses or mirrors and tracking systems to focus a large area of sunlight into a narrow beam.

Energy: is the capacity of a physical system to do work. Energy exists in several forms, such as, heat, light, mechanical, electrical, and kinetic.

Photovoltaic: a type of technology which uses a device (usually a solar panel) to produce free electrons when exposed to light, thus resulting in an electric current.

Renewable Energy: is energy obtained from natural resources, such as, sunlight, wind, rain, tides, and geothermal.

Solar Cell: is any device that converts the energy in light into electrical energy through the process of photovoltaics.

Solar Chemical Process: uses solar energy to drive a chemical reaction. Such processes offset energy that would come from a fossil fuel source.

Solar Energy: is the energy received by the earth from the sun. The energy is in the form of solar radiation which makes it possible to produce solar electricity.

Solar Panel: is a device which is used to convert the energy contained in the sun's rays into electricity.

Chapter 20

Project-Based International Collaboration in Solar Energy Education: A Case Study from France

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ABSTRACT

This chapter describes a project-based international collaboration in renewable energy systems design and implementation. The collaboration involves several educational institutions in Europe and USA. Working in teams, the undergraduate students at the partner institutions gain valuable experience in renewable energy systems design and construction. The participating students also learn effective teamwork and project management skills.

INTRODUCTION

Renewable energy is becoming increasingly important as an energy source. The key forms of renewable energy include solar, wind, hydro power, biomass, biofuel, tidal waves, and geothermal (Anwar & Favier, 2011). Renewable energy serves as a replacement of depletable

energy sources, such as fossil fuels, in many energy applications. The renewable energy usage areas include power generation, hot water/space heating, environmental monitoring and transport fuels. New applications of renewable energy are being constantly developed. Thus, research and development aimed at harnessing renewable energy sources is increasingly assuming an important role in the development of our society.

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In France, use of renewable energy has long been focused on the generation of electricity from wind farms and solar panels. Another focus area for renewable energy usage is cogeneration, a process of simultaneous production of electricity and heat from natural gas, biomass, waste products, coal, and petroleum products. Biomass is the leading source of renewable energy used in France. In addition, hydroelectric power has been used in France on an industrial scale since the beginning of 20th century.

The French national energy policy calls for an achievement of a 50% increase in the production of heat from renewable energy, by 2015. Thus, France is actively supporting energy-related research, development, and innovation. French national energy research strategy focuses on energy efficiency, energy storage, solar energy, biofuels, and sea-based energy systems. The key objective of this strategy is to obtain greater energy efficiency from all technologies and to develop alternatives for fossil fuel based technologies. The French Agency on the Environment and Energy Management (ADEME) is supporting and coordinating research and development focusing on energy, air and soil quality, and the management of wastes and noise. The priority themes around which ADEME has established its research programs are as follows:

- Ecologically responsible production and consumption.
- Sustainable cities and regions.

The major research programs based on the above mentioned key priorities include:

- Green buildings
- Environmental assessment
- Socioeconomic forecasting
- Green transportation
- Bioenergy and bioproducts
- Generation of electricity from renewable energy resources

- Smart grids
- Energy storage

Following the French national energy research strategy, research is being conducted in the universities, public scientific and technological institutions, public and private industrial organizations, and public-interest foundations throughout France. In addition, many academic institutions in France are taking steps to integrate the renewable energy concepts into their curricula. One such institution is IUT Bethune of the Université d'Artois in northern France. The IUT Bethune electrical engineering students learn the renewable energy concepts and applications through a project based international collaboration in engineering education. The subsequent sections in this chapter describe this international collaboration in renewable energy education and research. The driving factors for this collaboration are also listed. Moreover, obstacles faced in implementing this education and research collaboration are explained.

COLLABORATION FRAMEWORK

International engineering design collaboration can be implemented in more than one forms. It may be a parallel design program in which the students at two or more participating institutions located in different countries work on the same engineering design problem. It may also be a program in which students work together on a single international design team and visit each other during the academic year (Anwar, Favier, & Jouglet, 2008). Several examples of both above mentioned forms of international academic collaboration are described in (Hill & Pena, 2010, Apple-Smith, Miner, & Riha, 2006; Heitmann, 2006; Hager, 1998; Hansen & Andersen, 2002). Both forms of international collaboration have been used by IUT Bethune. The goals of design projects conducted through the above mentioned international collaboration are as follows:

1. Undergraduate engineering students enrolled in different educational institutions in France, USA, Ireland, Poland, Romania, and Hungary will design and implement a common renewable energy system design project.
2. Students will gain valuable experience in multidisciplinary teamwork and project management.
3. Participating engineering students will gain experience regarding the modern reality that many times one subsystem of a renewable energy application is developed in one country and the other one is developed in another country.
4. The collaborative team-based design project will link multiple students' teams over international borders.
5. Students will develop a good understanding of solar energy systems in an international context.

The international collaboration between IUT Bethune and the several educational institutions in Western and Eastern Europe is meant to create an early awareness of the global implications of renewable energy education. The partners in this international collaboration include:

- IUT Bethune, Université d'Artois, France
- Dublin Institute of Technology, Dublin, Ireland
- Warsaw University of Technology, Warsaw, Poland
- Cluj Napoca University, Cluj, Romania
- Kando Kalman Faculty, Budapest, Hungary
- The Pennsylvania State University, Altoona College

IMPLEMENTATION OF THE PARALLEL DESIGN FORM OF INTERNATIONAL COLLABORATION

During the year 2007 – 2008, the international collaboration was in the form of a parallel design project in which each educational institution pursued its own engineering design itinerary but all the partner institutions used the same problems and design objectives. The program involved the faculty mentors at all the partner institutions developing common project goals and design procedures and the participating students exchanging information on a regular basis through the use of Internet. The common project was titled "A Renewable Energy System for an Agricultural Farm". The project consisted of designing the electrical power system of an agricultural farm using different renewable energy sources including photovoltaic panels, a wind turbine, and a small hydro-electric station. It was specified that the farm would be connected to the national grid to make it possible for the energy to be sent back to the national electricity supplier.

Different subsystems in this renewable energy application were designed and implemented by the partner institutions. The subsystem design task was assigned as follows:

- The subsystem designed and implemented by the Dublin Institute of Technology undergraduate electrical engineering students consisted of a water tank filled up by an electric pump powered by renewable energy sources. The students were required to measure the water level and send the measurement data to the central system so that the pump could be controlled.
- The undergraduate electromechanical engineering technology (BSEMET) students at The Pennsylvania State University, Altoona College developed Motorola 68HC11 assembly language based software to control the sump pump connected

to the power grid of the renewable energy system.

- The IUT Bethune undergraduate electrical engineering students assembled an energy system with photovoltaic panels and special inverters to send the electrical energy to the power grid. To achieve this task, the IUT Bethune team used 36 amorphous silicon solar panels, mounted on an aluminum frame, and fastened on a wall facing south.
- The Kando Kalman Faculty undergraduate electrical engineering students designed the charge regulator for the renewable energy system.

Teams consisting of 2-3 students each were formed at all the participating educational institutions. Preliminary technical specifications regarding the above-mentioned renewable energy system were provided to the student teams. Each of the student teams was assigned a faculty mentor. The faculty mentors guided their respective teams throughout the duration of this project. The faculty mentors in the different educational institutions collaborated with each other to make sure that the teams were progressing towards the attainment of the project goals. The mentors also jointly developed the instruments to assess students' teamwork.

The driving factors for the above mentioned international collaboration were as follows:

1. **Committed Faculty Mentors:** At least one faculty member at each of the partner institutions was responsible for mentoring the undergraduate students' teams at his/her respective institution
2. **Endorsement from the Management at the Partner Institutions:** The academic administration for each of the participating institutions endorsed the above mentioned international collaboration
3. **Motivated Undergraduate Students:** The undergraduate student teams at the partner

institutions demonstrated a high degree of enthusiasm in carrying out the team tasks.

IMPLEMENTATION OF THE SINGLE TEAM FORM OF INTERNATIONAL COLLABORATION

During 2009 and 2010 the international collaboration among the partner institutions was in the form of a single team consisting of undergraduate electrical engineering students from France, Hungary, and Romania working under the guidance of one faculty mentor at IUT Bethune. Students also received technical guidance from the co-faculty mentors at their respective educational institutions. During the above mentioned period of time, two different teams of students from France, Hungary, and Romania, conducted the following renewable energy design projects:

1. Design and construction of a microcontroller based solar heating system.
2. Design and implementation of a microcontroller-based protection system for solar walls.

The first capstone design project, conducted in 2009, consists of designing, constructing, and testing a solar system used to heat fresh air. The system used solar energy obtained through a 10-watt photovoltaic panel to supply its electronic subsystem and its actuators. The system is implemented using a flat box with a glass pane on top exposed to sun light. The box is constructed using plastic and glass fiber materials with a thermal insulation to increase the efficiency. The inside surfaces of the box are painted black to capture the maximum solar energy. The fresh air is injected through an intake tube into the heating space. An outlet tube directs the heated air to the outside process. A fan is used to accelerate the air flux. The electronic subsystem controls the fan using information from temperature sensors.

The above mentioned solar heating system has been tested under the sun light. The inside temperature rises quickly and can reach above 60°C. At this point, the fan is running and it ventilates hot air toward the outlet tube. This microcontroller based solar heating system provides a good demonstration of environmental sustainability and green energy management.

The second capstone design project was conducted in 2010 and it involves a solar wall capable of transferring solar energy into a special brick to store energy in the form of heat. The bricks of this solar wall get warmer upon receiving energy from the sun. As the wall gets warmer, the hot air flows in an upward direction to warm up the space. To prevent the air circulation in the opposite direction, an electrical gate is installed for the cold air intake. The solar walls constituting the wall contain a plastic envelope which melts if the wall temperature gets too high. To resolve this issue, an electric shutter is installed next to the wall. The project focuses on the design and implementation of a microcontroller based automatic control system for the shutter.

The above mentioned capstone design projects conducted by the international student teams at IUT Bethune during 2009 and 2010 allowed students to achieve the following objectives:

1. Students learned the fundamental concepts and the practical applications of solar energy in an international context.
2. Students developed the ability to analyze characteristics and operational principles of different energy conversion mechanisms.
3. Students learned how to use appropriate hardware and software to meet their project requirements.
4. Students learned how to effectively communicate design and test results in written reports and oral presentations.
5. Working in multinational teams, the students learned effective teamwork skills.
6. Students gained useful project management skills.

CONCLUSION

An international renewable energy systems design collaboration between IUT Bethune, France and several partner institutions from Europe and USA was described in this chapter. During the first year of this collaboration, the student teams in the partner institutions worked on a common engineering design project. Each institution was responsible for the design and implementation of a specific subsystem. Then, all the subsystems were integrated into a complete functional renewable energy system.

In the subsequent years, this international collaboration has evolved into the form of a renewable energy system design project conducted at IUT Bethune by a multinational team consisting of students from partner institutions in Europe.

The international collaboration has helped the participating students understand the renewable energy systems applications in an international context. It has also helped students develop skills to effectively function in multinational teams.

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KEY TERMS AND DEFINITIONS

Capstone Design Project: Is a large-scale design project meant to fulfill the last requirement for an undergraduate degree in engineering or technology.

Energy Conversion: Is the process of changing energy from one form to another.

Hydroelectric Plant: Is an electricity generating facility that uses the mechanical motion of water to create power.

Inverter: Is an electronic device that reverses the sign of the current or voltage.

Photovoltaic Panel: Is a packaged interconnected assembly of solar cells.

Solar Heating: Is the conversion of solar radiation into heat.

Teamwork: Is the process of working collaboratively with a group of people to achieve a goal.

Wind Turbine: Is a rotary device from the wind.

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