SOLAR ENERGY

TECHNOLOGIES AND PROJECT DELIVERY FOR BUILDINGS

ANDY WALKER, PhD, PE

RSMeans

WILEY

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This book is dedicated to practicing mechanical, electrical, and plumbing engineers.

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The team of RNL, Pinkerton Construction, MKK Consulting Engineers, and energy and sustainability consultant Ambient Energy incorporated extensive photovoltaics, daylighting, and solar orientation into the 105,000 sf Central Platte Campus for the City and County of Denver's public works department.

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FOREWORD

This book provides practical information for engineers and contractors involved in the design, cost estimating, and construction of solar energy systems. The material covered in the book will enable a professional engineer to design buildings that are more energy efficient. It provides the information necessary to integrate solar features, such as hot water heating, passive design, and photovoltaics, into the development of individual homes or commercial buildings.

The topics covered in the seven chapters of the book begin with an overall description of the solar design process, followed by a chapter on the solar energy resource that includes maps and equations for solar positions as a function of time, location, and orientation. Basic material is provided on the use of solar energy for producing electricity, hot water, and space heating. The last chapter contains case studies of successful solar buildings in Colorado and Nevada.

The overall level of presentation makes the material accessible to anyone with a basic engineering education. Although a background in heat transfer, fluid mechanics, and economics will be helpful, the book does cover the elements of these topics and gives references for the reader to obtain more detailed background information.

A most useful feature of the book is that it approaches the design not from an academic but from a practical engineering perspective. It includes both simple calculations and descriptions of more sophisticated computer tools to analyze solar systems, including performance and economics. Many neophytes in the design of solar systems will find these practical features and tools to estimate the performance of different systems, such as, for example, a photovoltaic electric system, most useful. The book is clearly written and amply illustrated with both schematic diagrams and photographs that will help the designer visualize the end-product in a realistic setting.

In summary, *Solar Energy: Technologies and the Project Delivery Process for Buildings* combines the expertise of the author's thirty years of experience with up-to-date data on climactic resources and current computer programs useful to the practicing engineer for analysis and design of solar buildings. With climate change and energy efficiency becoming the focus of the future of buildings and energy planning, this book will be an immensely useful reference for practicing engineers to integrate solar thermal and photovoltaics into building design.

Frank Kreith

BIOGRAPHY OF FRANK KREITH

Dr. Frank Kreith has taught at the University of California, Lehigh University, and the University of Colorado, where he is now professor emeritus of engineering. From 1988 to 2001 he was the American Society of Mechanical Engineers International (ASME) Legislative Fellow for Energy and Environment at the National Conference of State Legislatures (NCSL), where he provided assistance on energy, transportation, and environmental protection to legislators in all fifty states. Prior to joining NCSL in 1988, Dr. Kreith was the chief of thermal research at the Solar Energy Research Institute (SERI), currently the National Renewable Energy Laboratory. During his tenure at SERI, he participated in the Presidential Domestic Energy Review, served as an energy adviser to the governor of Colorado, and was the editor of the *ASME Journal of Solar Energy Engineering*. He is the author of over a hundred peer-reviewed articles and of textbooks on heat transfer, solar energy, and transportation. He is the recipient of the Charles Greeley Abbot Award from the American Solar Energy Society and the Max Jakob Award from ASME-AIChE, and in 1997 he received the Washington Award for "unselfish and preeminent service in advancing human progress." In 1998, Dr. Kreith was awarded the ASME medal for research, publications, and public service, and in 2004 he was named ASME Honorary Member. In 2005 the ASME established the Frank Kreith Energy Award, in recognition of Dr. Kreith's contributions to heat transfer and renewable energy. He now teaches an honors course on sustainable energy at the University of Colorado and has published a textbook on this topic.

PREFACE

In this book I draw upon thirty years of experience in solar energy engineering to prepare the practicing engineer to deliver solar energy systems in their projects. I try to include between the covers of this book all of the information specific to solar energy needed to supplement the general project delivery process of a mechanical, electrical, or plumbing engineering company. When used with conventional design processes, codes, and standards, this book enables a design professional to include photovoltaics, solar water heating, solar ventilation air preheating, and passive solar heating features in the design of buildings.

As associate editor of the *Journal of Solar Energy Engineering* and more recently as technical and general program chair for the ASME Energy Sustainability Conference in 2009 and 2011, I have studied a lot of literature on the topic of solar energy engineering. I've tried to limit the material in this book to only the information that the practicing engineer needs to incorporate solar energy measures into building energy systems. The first chapter is an introduction to the process by which solar projects are delivered and issues to think about when integrating the intermittent solar resource into the conventional energy systems of a building. The topics covered in the subsequent chapters of this book include the quantity, timing, and quality of the solar resource and descriptions of technology and applications specific to photovoltaics; solar water heating; solar ventilation air preheating; passive solar heating, and cooling load avoidance. Many practical examples have been included. Each chapter covers the operating principle of the technology, the major components and how they are arranged in systems, simple calculations of system cost and performance, recommended software for more detailed design and analysis, sample procurement specifications, and case studies of each technology deployed in different applications. Example calculations are included in each section. Each chapter ends with case studies specific to the technology of that chapter, and the book includes a special chapter in color that highlights the features of three solar buildings in more detailed, multi-disciplinary case studies. The intent is to provide comprehensive information through all stages of implementing a solar energy project.

I've done my best to provide accurate and useful information in this book. But codes and standards change frequently and are subject to differing interpretation. Therefore, all information here must be presented as my opinion, or my understanding of a situation and its requirements, rather than as instructions or guidelines for a user to follow specifically. All sources of detailed information are referenced, but the reference may be incorrect or my interpretation or use of the information may be incorrect. The possibility of errors or omissions in the equations, tables, and text of this book may not be eliminated. Therefore, when using this book to help you deliver solar projects, it is your responsibility to make sure that the information of the book is applicable to your situation and applied correctly. Consult the authority having jurisdiction in your area for all requirements and questions related to applicable codes and standards.

To the extent possible, I've tried to include the names of companies and products, as well as information that might relate to the cost and performance of these products. Please be advised that no list of companies can be complete or up-to-date. Mention of a specific company or product should in no way be understood as an endorsement of any product, and there is no attempt to state that any product is superior or inferior to any other. Performance parameters listed may not be the best or most recent offered by a supplier. New companies come into business, and existing ones go out of business every day, so including mention of a particular company is just to represent a snapshot of a particular experience or reference, with the intention of familiarizing the reader with specifics of the current marketplace. Prices are reported in general and may not be representative of the cost encountered in the context of your project.

ACKNOWLEDGMENTS

I'd like to first thank the professors at Colorado State University Solar Energy Applications Laboratory who prepared me for a career in solar energy engineering: Allen Kirkpatrick and Byron Winn, who included solar topics in the coursework; George Lof, Richard Loerke, and my graduate adviser, Jane Davidson who served on my graduate commitee; and Bill DeCresentis who assembled the experiments.

I gratefully acknowledge the National Renewable Energy Laboratory as an institution and many of the staff there who have made it possible for me to pursue the passion that I have for solar energy, including managers Robert Westby and Nancy Carlisle and many esteemed colleagues. I gained much experience with solar energy projects by working with Anne Crawley and Boyan Kovacic of the US Department of Energy Federal Energy Management Program providing technical assistance to Federal projects. I thank Dave Renne of NREL for much that I know about solar resources, John Thornton for photovoltaics, Jay Burch, Russell Hewett, and Craig Christensen for solar water heating, Chuck Kutscher and Greg Barker for solar ventilation air preheating, and Doug Balcomb and Ren Anderson for much that I know about passive solar and building modeling. I thank NREL lawyer LaNelle Owens for obtaining approval for me to write this book and for providing permission to use NREL information in the book.

I appreciate my colleagues among the American Society of Mechanical Engineers Solar Energy Division who have been such a tremendous resource to me in my career: Jorge Gonzalez, Moncef Krarti, Eduardo Rincon, Aldo Steinfeld, Christian Sattler, Ming Qu, Jeff Morehouse, Frank Kreith, and many others. I'm especially grateful to Jan Kreider for being very generous with his information as I began teaching at University of Colorado at Boulder.

I thank the individuals who provided permission to use their material in the book and especially those who took time to share their experience and insights in the form of interviews that appear in the book. Thanks to Lauren Poole and Mary Azerbegi for reviewing the manuscript and for advice on proper writing. Thanks to Robert Argentieri, Amanda Shettleton and Amy Odum of publisher John Wiley and Sons for turning the proposition of this book into reality.

I thank my family, especially my wife Renee and my children Anna, Joshua, Alexander, and Kirby for the joy they bring and for their understanding in letting me take the time to prepare this book over the last eighteen months.

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Delivering Solar Energy Projects

Blazing overhead, the sun has always been an obvious source of energy. Early humans struggled against nature's numbing cold and wilting heat, flood and drought, predation and starvation. Newton and Einstein's understanding of force and energy has harnessed nature to elevate the life of the common man to a level of comfort that would have been envied by a prince of old. But the scale of this energy consumption has unintended consequences—the extent to which we are just now starting to find out about. All evidence is that primitive man bested nature in his struggle, and now, in a reversal, modern man must struggle to save nature's fragile life.

Solar energy contributes to that preservation effort, and this book can help you make a difference by using solar energy to reduce a building's demand on resources and its impact on the environment. Solar is clean and inexhaustible. It is distributed over the globe. Its availability is greater in sunny locations, but much of the world's population and expected growth is in those sunny areas. And in cold locations, there may be less sun, but there is a greater need for heating, so it is possible to use more of what solar heat is available.

HISTORY AND CURRENT USE OF SOLAR ENERGY

Solar has been used as a source of useful energy from early man, to the industrial revolution, and on into the space age. Hero of Alexandria is credited with inventing the first solar-powered water pump in the first century AD. A French inventor named Augustin Mouchot demonstrated a focusing solar reflector at the Universal Exposition in Paris in 1878 that he used to pump water, distill alcohol, cook food, power a printing press, and affect an absorption cooler to make ice. Remarkably, this same nineteenth-century inventor later used solar heat focused on junctions of dissimilar metals to create electricity and split water, producing hydrogen, which he stored as fuel. The inventors of semiconductor diodes at the dawn of the electronics age investigated solar photovoltaic cells as one of the first applications (Butti and Perlin 1980). And now, we find solar powering space satellites and vehicles exploring Mars. We take a closer look at the history of each technology at the beginning of each chapter.

Nowadays, the world runs on fossil fuels: coal, petroleum liquids, and natural gas. Figure 1-1 displays data from the *International Energy Outlook 2011,* an analysis published by the US Energy Information Administration, showing energy consumption of oil, natural gas, coal, nuclear, and other fuels from 2005 to 2012. Natural gas is seen to gain market share because it is a cleaner burning fuel and two extraction technologies (directional drilling and hydraulic fracturing) have increased supplies. Solar energy is counted among the "other" fuels and is increasing as well.

Of the 542 quads of energy consumed in 2012, solar accounted for only 0.1 quad. Figure 1-2 shows how that consists of solar thermal and photovoltaic applications in utility electricity, commercial uses, and residential buildings.

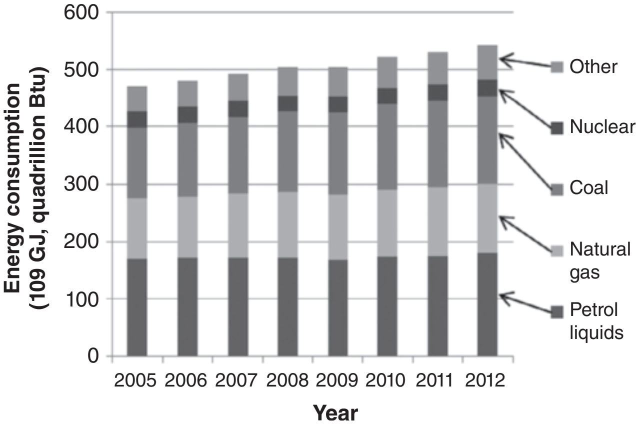


Figure 1-1. This chart of global annual energy consumption by fuel type (10^9 GJ, quadrillion Btu/year) shows the recent increases in the use of natural gas and renewable energy. (Figure by the author using data from US Energy Information Administration 2012)

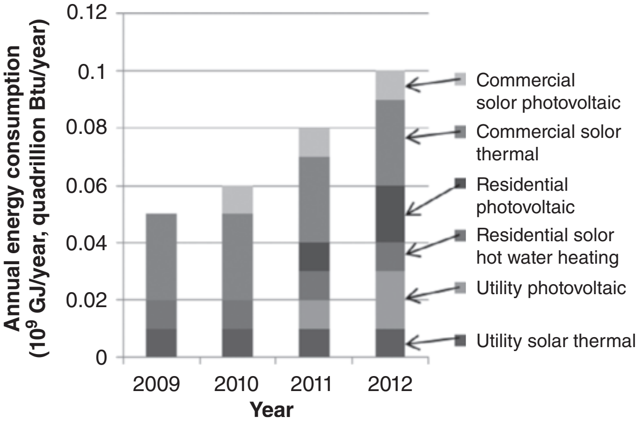


Figure 1-2. Global annual consumption of energy from solar energy applications has been increasing rapidly, with residential and utility-scale photovoltaics showing the most rapid growth. (Figure by the author using data from US Energy Information Administration 2012)

One may surmise that solar energy's contribution to world energy use is small, but what is exciting is that it is increasing rapidly. In 2012, solar electric generation increased 24 percent, a rate that has been sustained for several years now. On a percentage basis, solar is the fastest growing electric-generation resource. Figure 1-3 shows recent growth in solar electric generation capacity (GW of installed capacity) by country. For the years from 2010 to 2035, the US Energy Information Administration (EIA) predicts an average annual growth rate of 16 percent for utility photovoltaics and 11 percent for residential photovoltaics. According to this projection we should be busy designing and installing solar energy systems for some time to come.

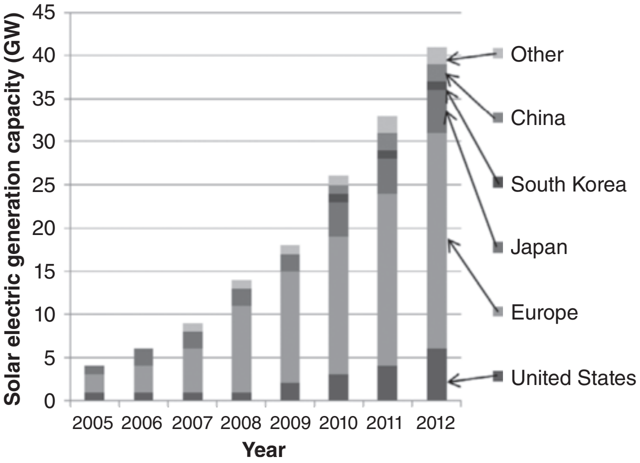


Figure 1-3. The cumulative generating capacity (GW) of solar electricity has demonstrated exponential growth, led by Japan and countries in Europe. (Figure by the author using data from US Energy Information Administration 2012)

ADVANTAGES OF SOLAR ENERGY

The main disadvantages of solar energy systems on a building are the high initial cost to purchase and install, ongoing operation and maintenance, and the risk of a failure in equipment performance. Solar also has many advantages that occur in a variety of ways to help us preserve the environment and meet our financial goals. In discussions among various stakeholders, the following advantages of solar energy are often cited:

Provide a Financial Return on Investment

Solar energy can be the least-cost option in a place where conventional energy is very expensive, such as in a location that relies on oil as a source of energy. Sunlight is delivered to even remote locations for free, so a solar project saves the cost of fuel, delivery costs, and cost of operating the conventional energy system. It is expensive to operate an electric generator in a remote location, and until 2004 such remote power applications were the largest part of the solar energy market. Since 2005, tax credits and other incentives have lowered the cost of solar energy projects to the point where utility cost savings (in not-remote locations) are sufficient to pay back the initial cost in the system with a favorable rate of return and manageable risk to the investor. Sophisticated investors serve the solar market—they combine utility cost savings, tax credits, and other incentives to construct cost-effective projects. Large projects involving third-party financing are responsible in large part for the growth in the solar market from 2005 to present.

Safety and Security of the Energy System

Solar is often added as a second source of energy along with conventional fossil-fuel systems. Depending on how the system is configured, this may serve as a redundant energy source. For example, the pump on my natural-gas-fired boiler recently failed, but I didn't have rush to get it fixed because the solar heating system provided the heat we needed. Solar electric systems may also be configured with batteries to provide power to dedicated circuits in a utility-power outage.

Recent news has been filled with tragedies related to energy. An offshore drilling rig exploded in the Gulf of Mexico, killing 11 workers and ruining the habitat with over 170 million gallons of toxic crude oil in 2010 (NRDC n.d.). Based on tracking plumes of isotopes such as iodine-131, accidents at nuclear plants in Fukushima, Japan in 2011 and Chernobyl Russia in 1986 will each be blamed for 500,000 deaths all over the world, mostly among infants less than one year old (Mangano and Sherman 2012). Little doubt remains that emission of carbon dioxide into the atmosphere from fossil-fuel use is causing a warming of the planet, with consequential changes in the climate. These catastrophic failures expose systemic distortions that high profits insert into the equation of risk versus reward (the profit being private, the risk being public).

I can't think of any way that solar could ever cause a disaster of such proportion. It is distributed and not concentrated into one facility. And while there are general safety issues related to electric systems and some hazardous materials in batteries and some types of solar collectors, solar involves no risk of explosion or of large release of toxic contaminants. While most solar systems are not designed to operate independently, they certainly can be, and if they are they contribute essential power in an emergency. Solar power systems don't require delivery of fuel in an emergency, such as a diesel-fueled generator would. Solar energy systems are located at the use of the energy, thus avoiding risk associated with failure of a large transmission and distribution system. The issue of safety and security spans all the way from an electrical outlet in a home in America to the Middle East. A complete calculation of the cost and risk of fossil fuels would have to include national security and international actions to secure stability in energy markets.

As a technological society, the tools that we have include education, incentives, and regulations; and we can use these tools to correct extreme risks before catastrophic failures occur and to limit the damage when things do go wrong.

WARNING

Safety First

Solar energy systems involve hazards encountered in any heating or electrical system, plus some encountered uniquely in solar systems. Safety should be considered during site visits, and in considering features of the design, special measures during construction, safety in long-term operation maintenance procedures, and safety in disposal of materials. General safety requirements on the worksite include helmet, safety glasses, vest, and work boots. Solar work requires long-sleeved shirt, long pants, sunscreen, and that the helmet be opaque and reflective. Roof safety is of particular importance. Roof safety usually limits access to the roof during site visits and requires different "fall protection" systems (railings, ropes) during rooftop activities and construction. Roof access for firefighters must be considered in consultation with your fire marshal when locating the solar collectors on a roof. Electrical safety applies to all parts of a photovoltaic system and entails two special characteristics of PV: 1) they are energized and cannot be turned off whenever the sun is shining and; 2) the short circuit current is not much greater than the expected operating current, so an arc can be sustained as electrical connections pull apart without tripping the breaker protecting that circuit against high current. "Arc-flash" protection is required when working on energized circuits and involves special gloves, as well as face and body coverings. "Lock-out tag-out" is a procedure to make sure nobody energizes a circuit someone else is working on. Sanitation is key to solar water heating systems, as they are often used to preheat potable hot water, and large volumes of water at tepid temperatures provide a media for bacteria, a risk that can be reduced by use of a load-side heat exchanger that does not store potable water. Some components used in solar energy systems involve toxic materials. The acid used in flooded batteries may be the most dangerous, but lead in batteries, cadmium in some types of photovoltaics modules, and spent heat-transfer fluid require custody over the life cycle of the material to properly recycle.

Less Pollution than Fossil Fuel

The myth persists that environmental damage may be "externalized" from cost in such a way that the profits are private but the damage is to the commons. The related deception is that the environment is limitless in its capacity to absorb pollution. The truth is that the environment is already at its capacity, and any further mistreatment has traceable consequences to human health. We are a technological society, so we can invent solutions to how processes interact with their surroundings. And we are civilized, so we can work together for the common good.

After hiking up to a rise above Everest base camp in Nepal, at 5.5 km above sea level (18,200 ft), I could look down on as much of the mass of the atmosphere as up. Almost half of the atmosphere's mass is below that elevation. The thinness of the atmosphere was visible on the horizon. Air pollution and radiation released anywhere are global in their reach and impact. This thin, fragile layer of air is our cabin-air on this spaceship earth. Pollution from technological activity has put a hole in the ozone layer, made rain more acidic, and warmed the atmosphere, risking the delicate balance that our only atmosphere has achieved and that we depend on. We need to take measures to check and reverse this degradation. Solar energy systems entail air pollution in their manufacture, shipping to the site, and installation effort. But once installed, every unit of solar heat or electricity delivered saves an equivalent amount of fossil fuel burned and associated emissions, plus it also saves losses in generating and delivering energy to the point of use. Solar energy may be viewed as one key strategy to reduce air pollution and associated climate change. Coal is mostly carbon, C, and a CO_2 molecule is released into the atmosphere for each carbon atom burned. Natural gas is CH_4, so for each molecule of methane, one molecule of CO_2 is also added to the atmosphere—but we also get the energy of the hydrogen converted to water so natural gas is the cleanest-burning fossil fuel. Reduction of carbon emissions may be attributed to solar energy delivery based on the heating value and the carbon content of the fuel avoided and the efficiency of the fuel-burning equipment. Utility companies report this performance data to regulators and often shareholders. Values vary from 1 $kgCO_2/kWh$ (2 $lbsCO_2/kWh$) for lignite coal with a heating value of 10 MJ/kg in a 33% efficient thermal steam cycle to 0.3 $kgCO_2/kWh$ (0.7 $lbsCO_2/kWh$) for natural gas with a heating value of 50 MJ/kg in 60% efficient combined cycle power plant. These calculations include that the CO_2 mass is higher than the fuel mass by the ratio of the molecular weight of CO_2 to that of C only: 44/12. Nuclear and hydropower generators don't have any carbon emissions. Standard values are adopted to administer uniform incentive and trading regimes, and are often calculated according to the mix of different types of generators in a utility interconnect, where the power is shared. A more sophisticated approach would identify the specific utility operation that changes as a result of the solar, often a move down the fuel consumption curve of a "peaking" gas turbine. Collecting a tax on the carbon emissions from the combustion of fossil fuels ($/ton of carbon) is one key strategy that is being implemented for mitigation of global climate change.

Statutes and Mandates

One good reason to consider solar energy is if a law tells you to. Language in the Energy Independence and Security Act, 2007, requires any new US federal government building to derive at least 30 percent of its hot water from on-site solar energy systems, and sets a declining scale for fossil fuel use such that by 2030 a new federal building would have to offset all of its energy consumption with on-site renewable energy. A previous law set a goal that the federal government get 7.5 percent of its electricity from renewable energy by the year 2013. Many other units of government have renewable energy goals or, more likely, carbon reduction goals, which on-site solar energy systems can contribute cost-effectively to.

Marketing Green Buildings

Solar energy systems differentiate sustainable buildings from the competition, and can increase demand over conventional construction. Many building owners are interested in incorporating solar energy for altruistic reasons, but energy cost savings and marketing help the bottom line. In a survey, 55 percent of buyers were willing to pay $5,000 to $10,000 more for green features in a new home (RS Means, 2006).

INCENTIVE PROGRAMS

Often an incentive program is what compels a consumer to install a solar energy system. Incentives are offered by units of government in the form of tax credits, tax exemptions, and tax depreciation and may be offered by utilities as rebates ($/Watt) or production incentives ($/kWh). Incentive programs are designed to make a project just barely cost-effective from the perspective of the building owner. Trends are for incentives to pay for production ($/kWh), rather than a rebate upon installation; programs phase out as they achieve their goals (often over 3 to 7 years); and programs require projects to compete for the available incentive amount. A liquid market has developed for Solar Renewable Energy Credits (SRECs), which utilities purchase from solar project developers or brokers to satisfy their regulatory requirements to use solar energy.

A very good resource to begin researching incentives available to a project is the Database of State Incentive for Renewable Energy at www.dsireusa.org.

Social Equity

In a technological society we realize that access to energy is a crucial interest, and in that way might be considered a human necessity, a human right, along with the way clean air and clean water might be. Every effort is made to deliver energy to those that pay the most for it, but there are almost 2 billion poor people on Earth without access to electricity. The well-being of society as a whole depends on affordable energy. As a resource distributed equitably to all, solar energy is able to meet the modest energy requirements of the least fortunate and provide some measure of social equity to the fabric of society. A distributed energy industry and infrastructure has social advantages, and solar, by virtue of being available directly to all, is less subject to cartel in the way an oil well or a nuclear power plant may be.

Economic Development

Every community has people working in the utility sector, but significantly more money collected through utility bills flows out of a community. The same amount of money spent on solar energy might involve local manufacturing and would necessarily employ local trades (electricians and plumbers) to install and maintain the systems. In 1925, the *Miami Herald* listed the Solar Water Heater Company as the seventh-largest construction company in Miami, an early example of the potential of the solar energy industry to create jobs (Butti and Perlin 1980). Many economic development authorities have high hopes for solar to bring jobs back into communities, and if solar were to be on every building, local jobs would certainly result.

Interview with Solar Entrepreneur Patrina Eiffert

Dr. Patrina Eiffert (pictured in Figure 1-4) is an internationally recognized expert and thought leader in the field of building integrated photovoltaic (BIPV) and field integrated photovoltaic (FIPV™) technology and holds numerous patents for related products. Dr. Eiffert was a pioneer in developing third-party financing for projects and she serves on the board of directors of four organizations: Women in Sustainable Energy (WISE), SolarFrameWorks Co., ImaginIt Inc., and Solar Angels.

Figure 1-4. "Solar Sisters" Patrina and Annett Eiffert at an installation of their "CoolPly" roof-integrated photovoltaic system at a football stadium in New England. (Photograph by Chris Bills, courtesy of Solar Frameworks.com)

You did your PhD dissertation on building integrated PV and now you are making a career in that field. What conclusions were you able to draw in your dissertation?

In the 1990s there were very few graduate programs specific to renewable energy, so I had to combine an undergraduate degree in economics with an architectural program to conduct research for my dissertation, "An Economic Assessment of Building Integrated Photovoltaics." The primary question was "Why would a building owner want to invest in a BIPV system?" In my research, I focused on the concept and value impact of avoided environmental emissions. This was probably the first doctorate in BIPV as well as the first identification of a potential market value for avoided environmental emissions for photovoltaics on buildings.

Did you know back then, when you were doing your dissertation, that you would start your own company someday?

My grandparents were Italian immigrants that came to America to start a new life in the 1920s. As a child I was always around the back rooms of commercial businesses such as a trucking business, grocery store, clothing boutiques and factories. Business was a part of life. Serving on the International Energy Agency Task on PV in the Built Environment gave me global exposure to multibillion dollar businesses and starting a business was a natural extension of that career. It has been more challenging and rewarding that I anticipated.

You've heard the saying "doing well by doing good"; how much are you motivated by profit versus saving the planet. Would you still do this if you weren't so successful?

Not only "doing well by doing good"—I was raised in the era of "dreaming big and making it happen." As a young girl I saw a man walk on the moon and tens of thousands of Peace Corps volunteers go to remote places in the world to contribute to improve the lives of others. Intellectually, I've always understood that solar must be a smart economic investment for the technology to be commercially viable. Fortunately, SolarFrameWorks has been consistently profitable from the beginning and also now in a very difficult economy. My motivation is based on the desire to contribute and help change the world. My sister and I were raised feeling empowered with a "can-do" attitude and the American spirit of innovation. We thrive on being technology leaders and working with the early adopters in different market segments. However, at the end of the day, we want our most important contribution to be through our 501 3-c nonprofit, Solar Angels, where we provide solar-powered lights, phones, and electronic equipment to remote health clinics.

Your products include roof-integrated PV (BIPV CoolPly Plus®), PV mounts that cover a landfill or brownfield (FIPV CoolPly Plus™), and special soap (PowerBoost®) to keep PV modules clean. Did these ideas come to you and then you found a market for them or did you see a need and then invent a solution?

Annett and I are strategic, and our goal is to assist in the commercialization of photovoltaic technology. The key question we ask ourselves every year is "What's next?" The ability to understand the needs of key stakeholders, understand where the technology and markets are now and where they may be going, presents Annett and I with all types of great product ideas. Years ago, as mothers of young children with solar careers, we got the idea for PowerFrames™, a plastic racking system, from the Lego® snap together toy. Investing dollars into market research, product development, market development is something we take very seriously. We are leading the way with Field Integrated Photovoltaics™ (FIPV) as we have done with Building Integrated Photovoltaics (BIPV CoolPly Plus®). When we created PowerBoost® solar panel cleaner, we laughed and called ourselves the "Molly Maids® of solar."

(continued)

At that time we saw that the market was going to incentives based on power production [$/kWh delivered], and keeping the panels clean with engineered detergent helps power production a lot. We have now sold over 20,000 bottles in the US, Australia, and Europe. Our next goal is to get this product on the shelves of big box retailers. We have a number of additional product ideas in our portfolio that we look forward to bring to the market. It's a shared passion for us.

Can you provide any advice to readers that might be thinking about starting their own company in the solar energy field?

There is so much work and innovation still to be done to commercialize solar technology. Everyone is born with certain God-given gifts and talents. It's your responsibility to truly understand who you are and share your gifts with the world. The competition is brutal and the work is hard. However, if you live in your talent, you can contribute to the solar industry and reap the personal as well as financial rewards.

SOLAR ENERGY PROJECT DELIVERY PROCESS

Goal-setting

Some organizations have set a goal as to what percentage of their energy they want to obtain from renewable energy, such as the 7.5 percent goal for the federal government set by the Energy Policy Act of 2005, or a goal of 15 percent set by a major brewer. But more often, solar energy projects are considered because they contribute to a more general goal, such as to minimize operating cost or to reduce carbon emissions. Any planning should have a goal in mind, and the nature and ambition of the goals usually shapes the development of any solar energy project. Goals are often designed to meet an optimal condition under constraints. For example, minimize carbon emissions under the constraint of same or lower cost; or minimize life cycle cost under the constraint of 20 percent carbon reduction. Planning can then figure out a way to approach that goal, but a thoughtful and inclusive process to set the goal comes first.

Team Building

A diverse team is essential to complete a solar energy project. Solar projects involve an energy manager or sustainability advocate who champions a solar project, a team, including a contracting official, facility planner, or facility manager, to contract for the system, and a team to install a system, including design engineer, equipment suppliers, installing contractors, and other agents. The goal and the plan to meet the goal decides who needs to be on the team, and it might involve a wide range of stakeholders, including other property owners in the area who can see your solar system, the local utility company, local planning and code officials, neighborhood associations, and any others depending on the particular situation. Every team member should state their understanding of the goal and their commitment to work toward it. A deer can easily outrun a lone wolf, but in a phenomenon called "heading off," one wolf chases the deer while another runs the hypotenuse to where the deer could turn. By running a shorter distance they are sure to catch the deer.

Screening

Some organizations operate a lot of real property in different locations, each with different solar resources, different utility rates, and different incentives such as tax credits. Many can point to successful solar projects on some of the buildings, often resulting from the interest of an on-site champion, but few have taken a structured approach to plan which set of solar technologies at which facilities can achieve their goal at the lowest cost. Simple calculations to screen a large number of sites for cost-effective project opportunities—photovoltaics, solar water heating, and solar ventilation air preheating separately—are described in (Walker et al. 2006). Subsequent work includes combining the effect of multiple technologies at a site, considering that you can't save the same kWh twice, and considering interactions between the technologies. An example of such interaction is that pumps and fans involved with the solar heating systems will be additional electric load and that a photovoltaic system could supply that electricity (Walker, 2009a). RETScreen is a free online tool for screening that is referred to repeatedly in this book (www.retscreen.ca). A screening calculation does often result in some details like how big a system should be, how much it might cost, and how much it might save—but the calculations are not detailed and not confirmed with a site visit, so a screening is not sufficient to inform a decision of whether to do a project or not. That requires a full economic feasibility study to establish the economic details and an engineering feasibility study to confirm that there are no technical issues that could prevent a project at the site.

A screening study involves collecting information without visiting the site. Information includes solar resource data, utility bills showing consumption and rates, incentives, true-south and orientations of building roof areas, land area, net-metering limits (kW), electrical panel rating and breakers, and any other information that can be collected without sending staff to actually visit the site. You should be able to estimate the electric load, hot water load, or ventilation air requirement before visiting the site. You might also be able to find out what requirements relate to wind speed and exposure at the site as well as seismic requirements. A screening should determine which jurisdiction a project is located in and what requirements of that jurisdiction apply (which versions of which codes). Much of this data may be found in an organization's real-property management database and in its utility-purchase database, or in publicly available data resources—which is fortunate because collecting original data is very difficult. The results of screening studies are often presented on a map with symbols that indicate "go" for properties where photovoltaics, solar water heating, and solar ventilation preheating would reduce life-cycle cost below those currently paid; and "stop" at locations where solar projects would result in higher cost. This calculation requires a value for the solar resource (kWh/m^2/day), which for screening purposes is accessed from databases such as those found at www.nrel.gov/gis.

Site Evaluation

The purpose of the site evaluation is to collect first-hand information and to observe site conditions. A detailed checklist is used to collect information from a site without visiting it, but a site evaluation is required to see the things you didn't know to ask about. A "task analysis" by NABCEP provides detailed lists of tasks that sales and technical staff would conduct (NABCEP 2011). Many companies have tried to save money by sending new staff to do the site evaluation, but have had to repeat the site evaluation with more experienced staff because information was incorrect or not obtained on the first trip. Preparation is key to an effective site visit. It is important to have a checklist of all the information that needs to be collected and the instruments to collect all that information ready to go with all required accessories and batteries charged. Items to remember include safety glasses, flashlight, pen with waterproof ink, pad with fill-in-the-blank checklist and adequate paper, sunscreen and hat to protect against sunburn, magnifying glass to read small labels, camera, current meter if you need to measure electric loads, noninvasive flow meter if you need to measure hot water use, heldheld wind-speed meter if you need to measure ventilation air duct velocity, roller wheel to measure distances, infrared thermometer or temperature probe, and a device (such as Solar Pathfinder or Solmetric SunEye) to measure effect of shading objects. Some general considerations and considerations related to photovoltaics, solar water heating, and solar ventilation air preheating are as follows:

> Roof array locations: material, type, age, and condition of roof; area, tilt, and orientation of available roof areas; measure shading; document structural framing of roof and condition/integrity. Obtain terms of roof warranty.
>
> Ground array locations: type of soil; area, degree and orientation of slope to the ground; location of underground utilities and obstructions (gas and electric lines, water pipes, and so on); measure shading.
>
> Location for balance of system: area for PV inverter, disconnects, and transformer; for solar hot water tank, pumps, and controller, for solar ventilation preheat fans; identify path and measure length for conduit or pipe runs from array to balance-of-system location; identify source of electric power for pumps and fans.
>
> Interconnection with conventional systems: identify voltage and current rating of electrical panel or other location where photovoltaic solar power could feed into building; record current rating of breaker protecting that panel; determine limits on solar power that can be supplied to panel or specify other interconnection based on code limits; identify additional equipment requirements such as new box for interconnection or transformer as required by utility interconnection policies; determine if network configuration will be compatible with back-feed of power at this location. Confirm level of solar penetration on the utility circuit and that the utility will accept power on that circuit when available from the solar.
>
> Installation issues: Determine access routes and hours for delivery and staging (lay-down) of materials, equipment, and tools. Identify any special crane access for lifting solar water heating collectors, and palettes of PV modules onto the roof. Consider means of moving heavy water tanks or inverters into a room in the building.

Solar Energy Projects in New Construction

It is much easier to integrate solar energy systems into the design of a new building than it is to retrofit an existing building. NREL has published a guide for making buildings "solar-ready," detailing a checklist of general and technology-specific considerations (Lissel, Tetrault, and Watson 2009). Provide for the safety features required to install and maintain the solar collectors in the design of the building. For example, if the roof is sloped, harness connections should be permanently built into the ridge of the roof. Careful layout of buildings on the site can leave unshaded areas for ground-mount of solar collectors. Arrange rooftop mechanical and communications equipment to leave unshaded areas on the roof for placement of solar collector arrays. Provide roof structure to support the loads of the solar collectors, on the order of 30 kg/m^2 (6 lbs/ft^2) weight, but often less. Specify a roof type that is easy to mount solar collectors on. Ballasted systems install easily on flat membrane roofs, and generally any required roof penetrations may be sealed by standard products and methods. For sloped roofs, standing seam metal roofs are expensive initially but have a low maintenance cost. They also are very easy to attach solar collectors to because of clamps that are used for attaching mechanical and electrical equipment to the seams without penetrating the metal pan of the roof. Shingles or tiles must be removed around a roof stanchion, and the stanchion flashed in to mate with the shingles or tiles, making these types of roofs the most difficult and expensive to attach to. Install any required blocking between rafters of a roof, for the solar mounts to attach to, before the ceiling is installed.

In new construction we can designate locations for the components of a solar energy system: water storage tanks, controls, valves, inverters, electrical switchgear. This space would be in optimal proximity to the solar collectors and the point of utility interconnection. Electrical conductors and water pipes should be arranged in the shortest route possible to save on initial cost and improve efficiency. Pipe chases may be made to connect the roof to the building electrical and plumbing systems with pipe or conduit, without having to run them in exterior walls or be surface-mounted.

Consider vertical wall area facing toward the equator for a solar ventilation air preheating system. Avoid placement of sources of pollution, such as boiler flue or truck loading dock, near transpired collector. Arrange openings in wall (windows) to allow easy layout of transpired solar collector. Add additional opening in the first stage of air-handling unit to allow introduction of solar preheated ventilation air.

Feasibility Study and Life-Cycle Cost Analysis

A feasibility study establishes that the project is viable financially and also able to be constructed with regard to any physical or technical constraints. An evaluation of cost-effectiveness involves a cost estimate of how much it will cost to install the system, an estimate of utility cost savings and operation and maintenance cost, and a life-cycle cost to reduce all these cash flows to their present value according to the discount rate. Some key elements affecting feasibility of a project include:

- Solar resources: evaluation determines the amount of solar energy available at the site.
- Utility rates: details of the utility rate structure determine the actual energy cost savings.
- Incentives: payments from utilities, state and Federal tax credits
- Load: load to serve directly or other “off-taker” of the solar energy such as an agreement with serving utility to accept solar power from a system.
- Authority to improve the property: Permits from local building authority; compliance such as historic preservation or viewsheds.
- Site control: Ownership, Lease, or Easement to the land or roof area; any rights-of-way that may be required to access the location.
- Interconnect agreement: terms under which the solar system may be connected to the larger utility system and operated.
- Financing: low interest rates are required when financing solar systems due to the high initial cost and long financing period.
- Bonds and insurance: availability of construction and payments bonds, and insurance—and at what price—affect project feasibility. Construction bonds are insurance that the contractor has sufficient resource to build the project and payment bonds are insurance that any subcontractors will be paid.
- Maintenance: local expertise must be available to perform maintenance and repairs

Life cycle cost analysis (LCCA) is the only way to evaluate solar energy projects because they are characterized by a high initial cost but then a low operating cost over the life of the system. Key terms involved in life cycle cost analysis include *discount rate*, d (percent/year); *inflation rates* for various fuels and *operation and maintenance costs*, i (percent/year); and the *analysis period*, N (years). Future costs are “discounted” down to their present value according to the *discount rate*, so that a solar project which has a high initial cost but a low operating cost may be compared to an alternative fossil fuel system that may have a low initial cost but a high fuel cost over its lifetime. Like all things in life, there is an ASTM standard on how to do life cycle cost analysis, and it entails: Standard Practices E 917, E 864, E1057, E1074, and E112; and Standard Guides E1185 and E1369. These standards have been codified into federal regulation 10CFR436, which requires federal agencies to use specified rates and methods so that life cycle cost estimated by different people in different agencies in different parts of the country could be compared. Many other agencies have adopted these standards or use them as the basis of their own methods. Siglinde Fuller, Amy Rushing and the Office of Applied Economics at NIST provide guidance and software products to implement life cycle cost analysis (www1.eere.energy.gov/femp/information/download_blcc.html). Costs considered include

- Initial investment cost, C_{initial} (\$)
- Energy cost savings, C_{savings} (\$/year)
- Operating and maintenance cost, $C_{\text{O\&M}}$ (\$/year)
- Costs to replace equipment (based on C_{initial})
- Salvage value of equipment at the end of the analysis period (based on C_{initial})
- Costs related to financing (based on C_{initial}).

Economic parameters involved in the analysis include

- Discount rate, d (percent/year), rate at which future costs are discounted to present value. If you would rather have \$0.95 today than \$1.00 a year from now, then your discount rate is 5%. If you would settle for \$0.90 today, then your discount rate is 10%.
- Inflation rate, i (percent/year), rate at which costs escalate from year to year.
- Analysis period, N (years), number of years in the analysis period, usually 25 years for mechanical systems and 40 years for building systems.

Life cycle cost analysis reduces all future costs to their present value so that they can be compared. The factor used to discount the costs depends on the discount rate. Continuing with our $d = 5$ percent example, a dollar of savings one year from now would be worth \$0.95, one two years from now would be worth \$0.9025, and one three years from now would be worth \$0.8573. The present value of an annually reoccurring cash flow that starts at C_{savings} in Year 1 and persists for the

Definition

Discount Rate, *d* (percent/year)

Would you rather have \$0.95 today or \$1.00 one year from now? If you said you don't care, that they are the same, then your discount rate would be 5 percent. If you say you would rather have \$0.90 today than \$1.00 one year from now then your discount rate is 10 percent. The *discount rate* is the "time value of money" and represents the *opportunity cost* of not having that money to invest in other investments if you have purchased a solar energy system. The discount rate chosen by an organization or an individual depends on the alternative uses that they have for investment capital. The federal government has a very low discount rate of around 4 percent, as determined by Treasury bills of a term similar to that of the solar project (25 years); financial institutions that finance solar projects have discount rates between 6 and 12 percent. Most corporations considering solar projects on their own facilities tell me to use a discount rate of 15 percent, and some relax that to 12 percent as a special consideration in pursuit of carbon reduction goals to help solar projects look more cost-effective. Homeowners vary quite a bit, but may use a discount rate of at least 20 percent to inform a decision to buy a solar system. College students tell me they have discount rates over 100 percent—they need their cash now to pay rent.

entire analysis period of *N* years, and escalates at a rate of *i* as the cost of fuel increases, and that is discounted to present value at the discount rate *d* is

$$PV = C_{savings}\frac{(1+i)}{(d-i)}\left[1-\frac{(1+i)}{(1+d)}^{N}\right] \tag{1-1}$$

The present worth factor, *PWF* (years), is a factor that we can multiply by the first year's savings to get the present value of the life cycle of savings.

$$PWF = \frac{(1+i)}{(d-i)}\left[1-\frac{(1+i)}{(1+d)}^{N}\right] \tag{1-2}$$

Example of Calculating Present Worth Factor

For example, the present worth factor for $N = 25$ years with a discount rate of $d = 5\%$/year and an inflation rate of $i = 2\%$/year is calculated according to the equation above

$$PWF = ((1 + 0.02))/((0.05 - 0.02))*(1 - ((1 + 0.02)/(1 + 0.05))\verb|^|25) = 17.5 \text{ years}$$

The present worth factor has units of years and reflects that the time-value of money reduces 25 years of savings to an equivalent 17.5 years.

The life cycle cost is calculated as the net present value of an alternative. The life cycle cost of a solar energy system would be the sum of its initial cost and its operation and maintenance cost times a present worth factor.

$$LCC = C_{\text{initial}} + PWF^{*}C_{\text{O\&M}} - PWF^{*}C_{\text{savings}} \tag{1-3}$$

The levelized cost of energy, LCOE (\$/kWh), is the annual cost of the alternative divided by the associated annual solar energy delivery, $E_{\text{solar,annual}}$ (kWh/year).

$$LCOE = \left(\frac{C_{\text{initial}}}{PWF} + C_{\text{O\&M}}\right) / E_{\text{solar,annual}} \tag{1-4}$$

The savings to investment ratio (SIR) is the ratio of life-cycle savings to life-cycle investment

$$SIR = \frac{(PWF * C_{\text{savings}} - PWF * C_{\text{O\&M}})}{(C_{\text{initial}})} \tag{1-5}$$

Where the energy cost savings C_{savings} and the operation and maintenance cost $C_{\text{O\&M}}$ could inflate at different rates. The return on investment (ROI) is the interest rate that would have resulted in the same net present value from the same initial investment. The ROI is best determined iteratively using a spreadsheet or computer program like BLCC.

Indicators of cost-effectiveness include lowest LCC (\$) among alternatives, LCOE (\$/kWh) lower than conventional energy, savings to investment ratio greater than 1.0, or rate of return greater than the discount rate. The feasibility study should determine if the results from a project could meet the owner's financial expectations.

A feasibility study should also confirm technical feasibility, including physical space on the ground or roof to mount solar collectors; condition and strength of roof; paths for conduit and pipe runs are feasible; construction may be completed considering on-going operations at the building; technical feasibility of feeding solar electricity into the existing electrical service, of supplying solar heated water into the building water heating system; and of saving fuel by preheating ventilation air. Aesthetic considerations are also technical, especially when they involve preservation of historic buildings or cultural resources such as viewsheds.

Secure Funding or Financing

The first place to find funding for a solar energy project is an organization's own capital improvement or operations budgets. However, many organizations have limited capital investment funds, and they apply a high "hurdle rate," or minimum acceptable financial rate of return, to decide whether to invest the funds that they do have. Most of the solar projects that I've been involved in have a return-on-investment of less than 10 percent. If an organization has a hurdle rate of 15 percent, as many companies would, there are two remaining possibilities: the organization could consider a return less than their hurdle rate in order to realize other benefits from the project, such as environmental benefits; or the organization could seek a financier with expectations less than 15 percent that may be able to finance the project. Such third-party financiers often take advantage of the tax credits and accelerated depreciation associated with a solar project, thus they are called *tax equity investors*. Because they can monetize the tax benefits and are satisfied with a return on investment lower than other organizations, such financiers are involved in most large solar projects.

When all the parties to the contracts are private parties, anything that does not violate law may be proposed. But when one of the parties is a government agency, that agency can only operate under "prescribed powers" and may only have certain specific legal authorizations to enter into certain types of financing arrangements. The Federal Energy Management Program facilitates different financing vehicles available to federal agencies (www1.eere.energy.gov/FEMP/financing/mechanisms.html). These include:

> Power purchase agreements (PPA): Building owner pays for power delivered from an on-site solar energy system owned and operated by a third party.
>
> Energy savings performance contract (ESPC): Payments to an energy service company (ESCO) for providing and installing a solar energy system are guaranteed to be less than savings in utility cost and associated operation and maintenance.
>
> Utility energy service contract (UESC): The same contract used to procure conventional power from the utility is amended to provide other energy services such as an on-site solar energy system.
>
> Enhanced use lease (EUL): Land-owner receives electric power or thermal energy from an on-site solar energy project as in-kind payment for lease on unused land.

Some details of tax equity financing arrangements are listed in (Walker 2009b). There are many choices to be made in structuring any kind of financing arrangement. A source of other funds, such as a rebate, may either be subtracted from the cost basis of the system, and thus not be subject of tax credit or depreciation, or if it is not subtracted from the cost basis, it would be taxed as ordinary income. Often a choice must be made to take a tax credit initially as an investment tax credit (ITC, $) or over a period of time as a production tax credit (PTC, $/kWh), which delays the tax on income into future years. A project developer may "sell" the project to the financing partnership and pay taxes on the difference between the fair market value and the cost basis as income, or the developer may "contribute" the project to a partnership in exchange for distributions paid by the partnership over time. Distributions are often taxed at a lower rate than ordinary income and defer the tax to future years, so the tax can be paid out of the distributions themselves and may improve the after-tax ROI of the project developer without reducing the ROI of the investor partner.

Interview with Solar Financier Marc Roper

Marc Roper (pictured in Figure 1-5) is vice president of sales and marketing for Tioga Energy, a solar PPA provider based in California. Prior to joining Tioga, Marc led the sales, marketing, and external affairs for Turner Renewable Energy; was vice president and board member for photovoltaic manufacturer SCHOTT Solar; managed residential market development for photovoltaic manufacturer AstroPower; and headed up renewable energy programs for the State of Colorado's energy office. Marc earned a master's of civil engineering with focus on renewable energy and building systems design, a BS in engineering physics, and a BA in music from the University of Colorado in Boulder. He is a member of the boards of directors of the Interstate Renewable Energy Council (IREC), the Solar Energy Industries Association (SEIA), the North American Board of Certified Energy Practitioners (NABCEP), the Solar Rating and Certification Corporation (SRCC), and PowerMark Corporation.

Figure 1-5. Marc Roper speaking at the opening of 4 MW power purchase agreement PV project at Hemet Unified School District in California. (Photo courtesy of Timothy Clark, Johnson Controls, Inc.)

Your company, Tioga Energy, doesn't sell solar systems but rather sells energy from solar systems under power purchase. Why?

Generally, commercial and institutional energy consumers want less-expensive electricity, a way to hedge against electric utility rate increases, and a means of operating in a more environmentally sustainable manner. PPAs offer these benefits, while eliminating the need to come up with the significant capital required to build a solar power system and then manage the construction, operation, maintenance, repair, and removal of that system over its lifetime.

We use the term power purchase agreement as if it is single agreement but it is really several, right?

The power purchase agreement is the core contract that relates to the long-term sale of solar electricity by the PPA provider to the consumer. However, there are numerous ancillary agreements that are often needed in order to secure incentives, protect an investor's interest in the solar power system, and ensure the unhindered operation of the system over the life of the PPA contract. Depending on the situation, these can include utility interconnection and net-metering agreements, site lease or license agreements, easements, state and/or local government incentive contracts, consents to assignment, and subordination and non-disturbance agreements with site lenders, and contracts for the sale of renewable energy certificates (RECs). Coordinating and developing this suite of agreements is another of the benefits of the PPA model (although some of them are necessary only for PPAs)—the PPA provider generally takes care of all of this.

The term of the PPA is long enough to pay back the investors, yet at the end of the term a customer does not own the system and has to renew or buy the system at fair market value. Why is that? Fair market value might be pretty high for a PV system that is still producing power right? Have you determined fair market value on any systems yet?

One of the things that make the economics of a PPA work for both investors and consumers is the IRS' 30 percent investment tax credit. This credit is available to the first owner of a new solar power system, and it effectively reduces the cost to build a solar power system and therefore reduces the rate that the investor must charge the consumer for electricity in order to achieve acceptable returns. However, in order for an investor to claim this credit, it must be clear that they own the system according to the rules of the IRS. Provisions in a PPA that would effectively allow the sale of the system in the future at a fixed price could cause the PPA to be viewed as an installment purchase agreement, and cloud the interpretation of who owns the system and who is eligible to take the tax credit. For this reason, every well-crafted PPA stipulates that future purchases cannot be made at less than fair market value. With regard to future fair market value, the farther into the future you gaze the harder it is to predict. Factors such as remaining life and projected future cash flows, replacement value, and resale value. It's too early to tell what this will look like at the end of a 20-year solar PPA, but I'd bet there will be a strong market for refurbishing and redeploying second-hand solar equipment emerging in about 15 years.

Stuff happens. What happens if your company goes out of business? What happens if my company goes out of business?

Power purchase agreements are based on the concepts of structured project finance, where the suite of contracts comprise the assets of a special purpose entity formed solely to carry out the obligations of the PPA and attendant agreements. The investor retains the right to step into the contract to cure defaults of the provider, and assign the contract to a new provider if necessary. The investor does take on the risk that the consumer will go out of business and won't be able to continue to purchase electricity. In order to reduce this risk, the investor typically has a very high standard of credit, and sometimes will seek easements that further protect its ability to continue to operate the system and collect revenue from incentives, the sale of electricity to the utility company or a new tenant of the building.

How do you see the market for PPAs evolving in the future?

PPAs have great potential to deliver distributed solar generation to a significant portion of the commercial and institutional electricity market. However, PPA financial structures are still relatively new and complicated by tax laws, the long-term value of solar power systems as an asset class is not well established, transactions and contract documents are not yet standard, and the regulatory environment for PPAs is not yet stable. In order for PPAs to become truly efficient and pervasive in the market, the market must mature to the point where entering into a PPA is more like getting a mortgage for a commercial building and less like financing a big power plant. We are making good progress on a number of fronts: standardizing contracts, lowering installed system costs, establishing more favorable policies for grid interconnection at the state level. These things, along with increased consumer and investor comfort with the technology and long-term value proposition of distributed solar generation, will ultimately lead to enormous opportunity and market presence for the solar power purchase agreement and derivative products.

Figure 1-6 shows the many relationships between parties in a large solar project and the various agreements between each. A project developer and a financier form a partnership agreement with the investor as the general partner and the project developer as the minority shareholder. This partnership collects payment ($) from an “off-taker” of the power (kWh) in a power purchase agreement, and the utility company may also buy excess power from the project. There would be an agreement with the utility company to allow electrical interconnection with the larger utility system. There would be a lease or an easement associated with use of the land on which the solar collectors are installed. The project developer may sell the renewable energy credits (RECs) to a broker or a utility company that needs them to progress toward their regulatory goals, and RECs are an important source of revenue to make solar projects financially viable. Taxes are paid on the dividends paid to each of the partners. The project developer and financier may switch positions in the partnership in a partnership flip. The investor can use the tax credits (“monetize” them) because she has many sources of income which result in a tax liability. The project developer, on the other hand, may not have other significant sources of income and may even be a special-purpose corporation set up just to do the solar project. Thus, in the early years of the project financing term, the investor will hold all the shares and exploit the tax credits and depreciation. After all the tax depreciation is claimed (currently six years), the partners switch positions so that the project developer holds most of the shares and receives dividends which enjoy a lower tax rate than income in the US. Thus a partnership flip delays payment to the project developer, but results in less tax being paid.

The important thing about approaching any financing arrangement is to have qualified legal and tax advice. The deal must be optimally structured in order to compete with other project developers, and that requires specialized knowledge of the tax code and each party’s tax situation. Analysis requires complete cash-flow analysis and a model of each party’s tax liability. All available alternatives should be considered, and each party agrees to participate based on the benefits to them.

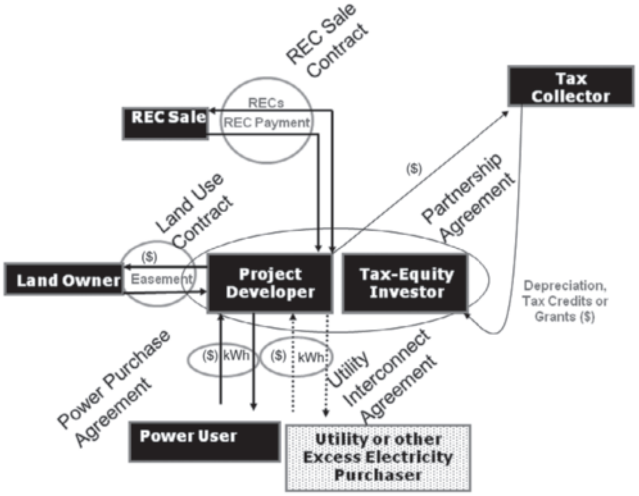


Figure 1-6. An example of the many relationships between parties in a financing arrangement for a large solar energy project is illustrated in this conceptual diagram. (Figure by the author, following those of Chandra Shah, National Renewable Energy Laboratory.)

Request for Proposals

A request for proposals (RFP) is a document issued by the building owner or project developer to solicit bids from solar suppliers and installers. The RFP may be advertised widely or may be sent only to invited offerors. The federal government advertises its project opportunities for bidders at Fed Biz Opps website (www.fbo.gov) with the intention of getting as many competitive bids as possible. This is how most suppliers find out about the sales opportunity, but it also frequent for suppliers to seek customers out with unsolicited proposals. A request for proposals should include:

Issuer: a clear definition of who is soliciting proposals and their authority to bind the owner of the building.

Performance requirements: what the project is trying to achieve in terms of delivered energy, emissions savings, or other desired outcomes.

Interface requirements: a description of the existing electrical, mechanical, plumbing, and other system that the new solar energy system must interface with in order to be able to delivery energy cost savings.

Compliance: who is responsible for complying with any regulations related to environmental, historic preservation, planning commissions, or any other compliance procedures? Who is responsible for obtaining any permits for construction and interconnection agreements for operation of a system?

Schedule requirements: required timeline to project completion. Urgent projects with short timelines should expect to pay a premium.

Information requested from offerors: technical approach to achieve the project objectives; technical qualifications (education, professional registration, certifications); past experience; references to contact from previous projects.

Selection criteria: offerors will address in their proposals the selection criteria stated in the RFP. An RFP may list out five or six different selection criteria, which may include technical approach; qualifications; and past performance. Selection criteria is perhaps the most important part of a project because if an owner gets a qualified and experienced team, then success of the project is almost certain; the obverse is also true.

Statement of work, also called scope of work: the statement of work must include all the tasks that the building owner expects the solar installer to perform. If an important activity is not in the statement of work, then the cost to perform that won’t be in the bid, and the contractor won’t have funds to complete that activity. To rectify that problem requires an expensive "change order." Language to make sure everything is included sounds like: "Contractor shall supply all services including design, construction management, installation labor and commissioning; and all hardware, supplies, materials, and appurtenances to make the solar energy system complete and operational." The statement of work should make it clear if the contractor is to manage compliance processes and associated permits or if the building owner will do that. The statement of work should make it clear who is responsible for improving any existing infrastructure to allow for the solar project. Any work that needs to be done to complete the solar project should be in either the statement of work document or among the expectations of what the building owners plan to do themselves or contract from other parties.

The proposals should be evaluated by a team according to the criteria laid out in the RFP. Careful review by very interested parties is essential to ensure that a good contractor is selected. One or more offerors would be requested to submit a "best and final offer" based on the details of the review and subsequent negotiations. Acceptance of an offer by the building owner signals the end of selection and the beginning of contracting.

Contract Documents

The statement of work from the RFP will be revised and become the statement of work for a construction contract. Contract documents involve many terms and conditions to make it clear how events or circumstances will be handled. For example, if it is determined during installation that a roof is in need of repair, who is responsible for that? The solar contractor or the building owner? Usually the building owner would be, and the roof repair would require a change order. The terms and conditions of the contract documents involve many important legal concepts including indemnification, payment bonds to insure that subcontractors will be paid, performance bonds to insure that the project is not left in an incomplete state, and statements of whether specific performance is required or if liquidated damages are paid when schedules slip or things go awry. It is essential here, when signing construction contracts, to have a well-proven document to start with, and full involvement and review of legal counsel.

Two common ways to structure the contract are "fixed price" or "time and materials" (also called "cost-plus" type contracts). In a fixed-price contract the building owner tries to make the contractor responsible for inaccuracies in the estimated cost and unforeseen circumstances that might delay work and increase cost. If the project is very simple and well understood, a fixed-price approach may result in competitive bids. But if there is any uncertainty in what it will cost to complete the project, a bidding contractor may either try to mitigate that risk by changing the contract language so that they are not responsible for it, or will have to charge extra to pay for that risk should it occur. In other words, with a fixed-price contract, you pay for contingencies whether they occur or not.

WARNING

Fraud in the Construction Industry

Fraud is endemic in the construction industry and solar is not immune. Examples of fraudulent contracting schemes that have surfaced on solar projects include:

- Accepting a down payment but then disappearing
- Accepting a down payment but then trying to find someone else to do it cheaper.
- Accepting progress payments but then not paying subcontractors.
- Paying cash to workers, thus avoiding income tax, employment tax, worker's compensation, and unemployment insurance.
- Inflating bills from subcontractors or forging invoices for cost-plus type contracts, or to claim a higher solar tax credit.
- Signing a request for an estimate that includes "office and legal" fees in addition to the cost of the estimate—and then fees ensue if you don't sign the contract.
- Theft from work premises, or personal information such as account numbers used improperly.

Solar companies are also cheated by fraudulent upper-tier contractors, suppliers, and even building owners. It is common for solar contractors to hear "you get paid when we get paid," from upper-tier or prime contractors, rather than to be paid according to the agreed-upon payment schedule. A building owner might inflate the cost to install a solar system in order to claim a larger rebate or tax credit, embroiling the contractor if there is a tax audit.

Investors in a manufacturer or installation company can also get ripped off—a PV company once sold its equipment and intellectual property to another company, profiting executives, but leaving investors with nothing.

Fraudsters prey on our own greed. They offer us deals that are too good to be true; and yet we believe them because we want to gain an advantage. The best defense against fraud is to check references. If the parties have a long track record of completing work on time and within budget, or paying for projects that they contract for, then that is the best indicator that they won't try to cheat. Recourse of a contractor against a building owner is a "mechanics lien," which gives the contractor an interest in the value of the improvements on the deed of the building. However, the best defense against fraud is prevention up front rather than relying on legal action to recover after damages have occurred, which is rarely fully effective.

Schematic Design

In a design-bid-build approach, the design is completed and then construction contractors bid on constructing that design. In a design-build approach, the installing contractor is also responsible for the design. Either way the design progresses through levels of decreasing options and increasing detail. Schematic design involves examining alternatives and doing an analysis to determine the size and type of major components. The design submittal includes drawings and equipment specifications, including a diagram, called a "schematic diagram," of all the major components and connections and interactions between the components and any existing building systems. The submittal would include the size and type of each component, any important component information such as efficiency, operating and control sequences, preliminary installation plan, and early identification of any safety procedures to involve or safety hazards to protect against.

This book should be useful in schematic design because it describes alternative ways to configure solar energy systems for electricity, hot water, or heating ventilation air and what major components are involved in such systems.

Design reviews should be conducted early in design, about halfway through design, and at the final design submittal. Comments from reviewers are only useful early in the design process; subsequent design steps only add detail to decisions already made. Reviewers should include building owner's representative, objective solar expert, operation and maintenance staff, utility staff regarding any utility interconnection, and the commissioning authority that will be responsible for commissioning throughout the duration of the project.

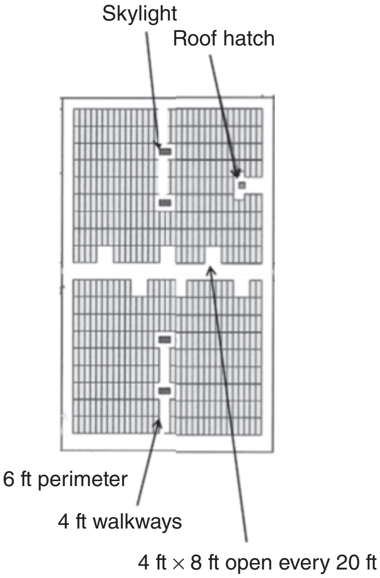


Figure 1-7. Leaving aisles open on the roof for access to existing equipment and skylights, and access required for firefighting, are considerations involved in locating the position of solar collectors on a roof during design development. (Figure by the author after those by US General Services Administration)

Design Development

Once the schematic design has been reviewed and agreed upon, the design team fills out detail according to the decisions made in schematic designs. Where the schematic design had size and type of components, design development adds specific manufacturers and model numbers. Design development reconciles all electrical or plumbing standards related to interconnections between components or control protocols used to communicate with components. The intention of design development is to add enough detail to the design, through narrative, drawings and specifications, so that anybody using those drawing would build the system the same way. Again, the developing design should be reviewed early in the process to confirm decisions before the design effort is expended filling out the details. For example, comments from a fire marshal would modify the access and laydown areas depicted in Figure 1-7 as the design is developed. A checklist to refer to when evaluating a design is included in (Stoltenberg and Partyka 2010).

Construction Documents

Once the design is completely developed, a final set of construction documents will be prepared by the design team. These consist of

- Narrative: text, photographs, and graphics describing the intent of the design
- Drawings: set consisting of site plan, roof plan, and structural, electrical, mechanical, plumbing, and controls drawings.
- Specifications: details of the requirements of each component.

This set of plans will be used for code compliance and permitting. There are no decisions remaining to be made in the preparation of construction documents—just adding detail regarding how the products are installed and connected. The installing contractor will begin construction using this set of plans, and will add shop drawings as particular assemblies are fabricated. The design team may also add "as built" drawings to reflect the details of the actual installation and any variances from the construction documents.

Construction Administration

Construction administration is a very detail-oriented profession. The construction manager will often stay on site and report back to the building owner regarding daily progress on construction activities. Proper timing and phasing is critical: equipment must arrive on site on time and needs to be installed in the right order. Financial damages may result if a subcontractor is not able to start work due to delays of another subcontractor. Upon failure of a window wall recently, the glass manufacturer blamed the mullion supplier, who blamed the installer, who blamed the window manufacturer. The construction manager must keep all the subcontractors working together as a team to deliver a successful project, so that they can all get paid.

The construction manager collects *requests for information* (RFIs) from subcontractors to clarify questions about how the design shall be implemented. The construction manager must also handle *change orders*, which are changes to the scope of work that result in changes to the schedule or budget. The owners may object to changes that cost more money, but quick resolution of disagreements is needed to keep the construction moving toward completion. All parties must be available or have delegates available to quickly respond during the construction period.

TIP

Change Orders and Requests for Information (RFIs)

During the construction process, the construction manager is busy requesting change orders and information from the building owner or design team. A change order is requested whenever any condition is encountered that was not expected in the RFP or in the contract. Say, for example, water damage to the roof deck is discovered during installation of solar collector roof mounts. The building owner may change the contract to pay the solar contractor for fixing the damage or may argue that repairing such damage was within the original statement of work and the contractor should fix it without additional pay.

It is a very common strategy among contractors to bid a low price, even lose money, to get the contract signed, but with the intention of making up for the low bid, and profiting more, with change orders as the project proceeds. Some contractors openly teach this tactic to their sales staff.

Requests for information are routine as long as they only seek clarification on design or building details, but they become contentious when the inquiry is to whether a lower cost material or component may be substituted.

Interview with Solar Project Manager Brett Jackson

Brett Jackson (pictured in Figure 1-8) manages solar energy projects as the Energy and Mechanical Engineering Program Lead for the Construction Facility Management Office of the Colorado Department of Military Affairs. He previously served as an Army Corps of Engineers officer. He has an undergraduate degree in mechanical engineering from the Colorado School of Mines and a master's in engineering management from the University of Colorado at Boulder. Additionally, Brett is a Professional Engineer, a Certified Energy Manager (CEM), a LEED-AP, and a Project Management Professional (PMP).

Figure 1-8. Brett Jackson at the Windsor Readiness Center, site of one of the solar energy projects that he is managing for the Colorado Army National Guard. (Photo by Michael Jaurrieta, courtesy of Colorado Army National Guard.)

The Colorado National Guard provides defense and emergency services in blizzards, floods, wildfires, search and rescue, and tornadoes. How does solar energy fit into that mission?

The Department of Defense has strategic sustainability goals aimed at lessening our dependence on foreign fossil fuels. In addition to energy load reduction, we feel that a renewable energy portfolio for energy source offset provides a robust approach to achieving this reduction. Regarding our mission to support the state and local communities during times of natural disaster, when the likelihood increases that power will be offline, we and the DOD are exploring ways to allow grid-connected PV systems that can remain operational when there is a loss of power.

What goals has the Colorado Army National Guard set with regard to renewable energy use, and how did you go about deciding on a goal?

The Colorado Army National Guard has established four sustainability action plans, one of which is centered on renewable energy generation. Through this action plan, it is our intent for our organization to be a net-zero electrical consumer by 2030. Our 2030 date was based on the Executive Order 13514 requirement that all federal buildings built by 2030 meet the net-zero-energy building requirement.

You've completed several solar projects—which are you most proud of and why?

We are very proud of our 172 kW PV system that was completed in August 2010 at our Grand Junction Field Maintenance

(continued)

Shop. This was our agency's first PV system and it was designed and built without a single change order. Additionally, what makes this PV system special is that when we built the maintenance building a few years before we installed the PV, we had designed into the building the necessary conduits as well as the upsized electrical switchgear, enabling all the PV project money to go into the PV panels and not into the building infrastructure. Through the efficient use of project funds, we were able to turn what was supposed to be a net-zero electricity system into a system that produces 20 percent more electrical energy than the building consumes.

What would you warn someone starting a solar project to watch out for?

When a solar project is being considered, be prepared to defend the project, as there will be many naysayers who raise objections that the project can't or shouldn't be done. Many times the solar project will be competing with other corporate projects/priorities. Complete a comprehensive life-cycle cost analysis and gain all the necessary stakeholders' involvement and support as early into the planning as possible. Finally, two items that can totally derail a solar project are an overestimation of the applicable electrical demand (kW) savings [as opposed to energy (kWh) savings] and also overestimating the payments obtained for Renewable Energy Credit (REC) payments.

Commissioning

Commissioning is formally confirming that a system is operating as intended, but the independent, third-party commissioning authority should be involved very early in design. First, the commissioning authority must fully understand the intent of the design, but also may add to the design in terms of instrumentation and controls required for monitoring and operation of the system. The commissioning authority should be involved in the review of each major design submittal (25 percent design, 50 percent design, etc). Standards related to commissioning of solar systems are described in each chapter (photovoltaics, solar water heating, and solar ventilation air heating), and they usually have three parts: physical inspection, solar array testing, and whole-system performance test. Physical inspection is to see that the system was installed as designed and that there are no mistakes in the installation. Of special interest in the inspection is to check that all specific code requirements and safety concerns that apply have been satisfied. This is facilitated with checklists that are specific to the type of system being inspected. Array testing measures the energy delivery of the array and the coincident solar radiation to assess the performance of each segment of the solar collector system, and the whole-system performance test tracks performance over a period of days to document all changes in modes of operation and overall solar delivery efficiency.

Long-term Monitoring and Verification of Performance

Some level of long-term monitoring is recommended for all projects. In order to deliver their cost-effectiveness, solar energy systems must operate for a very long performance period (25 to 40 years). Without some indicator of system performance, building owners would not know that their system is in need of repair.

Guidelines for the monitoring of solar energy systems describe several options, depending on the needs of the project participants (Walker et al. 2003). Options are described in four categories:

1. Determining the capability of the system to deliver solar energy as designed based on a detailed inspection of the system;
2. Measuring the energy delivery of the system with a meter;
3. Inferring the performance of the solar energy systems by analysis of utility bills; and
4. Calibrating a computer model of a solar energy system based on a short-term (one day) test.

There are different types of solar energy systems, but they have one thing in common that distinguishes them from energy efficiency measures—they supply energy rather than reduce energy use, and the supply, whether it is electric power, hot water, or heated air, may be measured directly with the right instrumentation. To meter the output of a solar energy system is thus the preferred monitoring option. The power delivery of each type of solar energy system may be measured as a flux multiplied by a potential:

- For photovoltaics, current (amps) is multiplied by the delivered voltage (volts), measured at the location that solar power is interconnected into the building power system.
- For solar water heating, it is mass flow rate of water, multiplied by the specific heat of water (kJ/s/C) and multiply by the temperature difference (C) between the cold water coming into the solar preheat system and the preheated water being delivered to the conventional water heating system.
- For solar ventilation air preheating, it is mass flow rate of ventilation air, multiplied by the specific heat of air (kJ/s/C) and the difference between the temperature (C) of the ambient air and the temperature of the preheated air

being delivered to a room or into the conventional ventilation air heating system.

- The measurement and verification program should be designed with an audience in mind. As much as possible reports should be "pushed" to interested parties: building owner, manager, utilities procurement contact, operations and maintenance managers, and even to the staff and visiting public through lobby displays.

INTEGRATION OF SOLAR ENERGY INTO THE EXISTING INFRASTRUCTURE

Solar energy systems must integrate into existing systems on many levels. First, there must be physical integration into the building, then there must be operational integration so that the solar energy system actually does result in the maximum amount of savings in conventional energy; and finally the solar energy system must be integrated into the larger utility system in such a way that the entire system is safe and reliable and economic benefit for the solar system owner is maximized.

Physical integration refers to space for the solar collectors on the roof, space for balance-of-system components within the building, and integrity of the structural connections. Operational integration refers to the performance of the system, such as feeding solar electric power into the building electrical system, preheating water for the conventional heating system, preheating ventilation air for the conventional ventilation air handler. For example, a gas-fired furnace would have to be controlled to allow a space to be heated by solar energy before heating it with gas. Making sure that intermittent and somewhat unpredictable solar energy delivery actually results in a commensurate savings of conventional energy requires some care in design and controls (in short, the conventional system must be modified and reprogrammed to step aside and let the solar energy system serve the demand first, and engage only if solar proves insufficient).

Grid-Integration: Effects of Intermittent Solar Energy Sources on the Utility System

Integration of solar energy systems into the larger utility grid is also a topic of much research currently. At very low levels of solar energy use (say, for example, 5 percent of a building's annual energy use), the conventional energy system could accommodate the intermittent nature of the solar energy without any problems. However, as solar projects on individual buildings get larger, and the number of buildings installing solar increases, there are increasing effects on the larger utility system that spans all the way from the local meter to the electric generation plant.

Impacts on the local meter include reverse power flow. If the building is served by multiple power feeds from multiple substations, as large buildings often are for reliability reasons, then there may be ”network protectors” to prevent a backflow of power from the building to the grid. These are often marked with an "NP" on building electrical drawings. Such an arrangement limits the size of the solar system to one which never exceeds the load or and may require a programmable inverter to curtail solar power and avoid tripping a network protector.

Impacts on the local distribution system include the potential for voltage fluctuations; problems with voltage regulation equipment, and reverse power flows. Electric current flows from a high voltage to a low voltage. In order to push their current onto the utility systems, multiple inverters on a circuit increase their voltage, causing a high-voltage condition.

Impacts on the transmission system include increase in the cost of reserve transmission capacity caused by uncertainty in forecasts in solar power generation. At times transmission may be insufficient to convey the solar power or inefficient in its scheduling. Generation resources without matching transmission capacity may be curtailed when transmission capacity is unavailable.

At the level of the electric generating system (power plants), the ability to respond to changes in the output of large amounts of solar energy on the grid is limited by the *ramp rate* of generation equipment. The ramp rate is how fast the output of the generator may be increased. Improved forecasting could inform power plant operators of when clouds will shade the solar generators in an area, so that they would know to ramp up conventional generators in advance of the need for the power. The potential for a sudden decrease in solar power requires an almost equivalent amount of *spinning reserve*. Spinning reserve is generating capacity that is already ramped up and ready to serve the load. Spinning reserve costs the utility money because it requires fuel to keep the generator spinning and maintenance required of the generator accrues by the hour not by the kWh. This is one of the arguments invoked by utilities as to why they shouldn't accommodate solar power or any intermittent generation. There are strategies discussed below to reduce the amount of spinning reserve required due to solar energy generators on the utility system during the day, due to intermittent clouds.

Utility system operation occurs at several time scales:

Power quality: Power quality refers to power factor (phase alignment of current and voltage waves), harmonic distortion (frequencies other than 60 Hz), and tolerances in voltage and frequency. The time scale of interest in power quality is less than one second. Electronic inverters are capable of delivering solar power to the utility with a power quality equal to or better than that of the utility grid as a whole.

Regulation: As the demand load (kW) on the electric system varies, the output of generators is controlled in order to maintain voltage and frequency. This occurs at a scale of seconds.

Load following: The output of a generator or system of generators is modulated in such a way to supply whatever load is imposed by utility customers at the time. This occurs at a scale of seconds and minutes. Forecasting the output of a solar plant through sky observation, modeling, or conventional weather forecasting provides advance notice that additional generation is required from other generators in order to meet the load.

Cyclic charging and discharging of storage: this is of principal importance in off-grid systems (using batteries) that don't have a utility connection where storage to serve several days of load is required, but is also conceivable in a large utility system. Intermittent solar energy could be put into storage and used later. Large battery systems are common in utility systems, but at large power levels they cycle in short time periods (minutes). In a sense, some measures to improve power quality involve storage, such as the capacitors to improve power factor. These have time-scale of 1/50 or 1/60 seconds, and storage is also very useful at longer time-scales: sub-seconds; minutes; hours; days; and even seasonal. Pumped-hydro storage is an example of a utility-scale storage that can store energy for a long period of time.

Unit commitment: As far in advance as is practicable, a combination of generators is planned to provide the expected load profile (kW over time). This planning of generators (also called *units*), is called *unit commitment*. Sophisticated computer algorithms to accomplish this planning have the objective of minimizing operating costs. Generators are scheduled to operate days, weeks, and years ahead, depending on the type of generator and the load profile. It is difficult for solar to play in this market because units are committed in advance and with a specified high level of certainty that the power can be delivered at the specified time. Forecasting the output of solar plants hours or days in advance is a technology that will enable solar plants to make some level of commitment to deliver power at a specified time.

All of this is conducted with the objective of minimizing cost for the utility system to deliver the energy, the reliability, and the environmental stewardship required by customers and regulators.

Utility Regulatory Policy

Utility companies provide a vital service to society. It is impractical to serve every customer with competing utility companies, and yet reliable energy is essential for survival in many climates. So governments allow utilities to operate as monopolies; and to prevent abuse, governments subject utilities to regulations, including how much they can charge for energy. The process of regulating them plays out in hearing rooms of state Public Utility Commissions (PUCs) across the country. Present in those hearing rooms are commissioners appointed by the governor of each state, their staff, the utility company, lawyers hired by large industrial energy users, lawyers hired by environmental groups or other "interveners" in a case, and a lawyer provided by the state representing consumers—each arguing why they should be entitled to more of the benefits of utility company operations and less of the cost. To "rate-base" a cost means the utility will collect that cost from all the ratepayers rather than only from those that benefit directly. If you are not in that hearing room…well then…you get what you deserve. The process only approximates fairness. For example, an environmental group might convince the commission to rate-base free energy efficiency audits for buildings; but the commission might then allow the utility company rather than the building owner to select the audit firm, thus broadening the hegemony of the utility and putting other firms that must charge building owners for audits out of business.

How does solar fare in this fray? Actually pretty well in many states, at least initially. Most solar projects these days benefit from a rebate ($/Watt) or production incentive ($/kWh produced by a solar energy system) paid by the utility in pursuit of goals set by regulators. These goals are often in the form of a "Renewable Energy Portfolio Standard" (RPS), which specifies that the utility companies operating in a state get a certain fraction of their energy from renewable energy. In order for this to benefit solar, which is often more expensive than wind, there has to be a "solar set aside" that ensures some of this goal be met by solar energy systems. Utilities have found that they can profit from this by installing their own solar power on their side of the meter. This results in large utility-scale plants to meet the regulatory goal. In order to promote "distributed generation" on each load, a program may require that the utility pay others an incentive to complete smaller projects in distributed locations.

Net Metering

"Net metering" is a utility policy that allows a solar energy system to deliver power in excess of the building load into the utility distribution system. Then, when the building load exceeds the solar delivery, the building draws power back from the utility. The monthly utility bill is calculated based on the difference between these two. Thus, in terms of the cost, net metering is like using the utility system as a battery but one that is 100 percent efficient and free. The benefit of net metering is that solar power generation saves fossil-fuel generators some fuel; but the savings in fuel might be less than the solar energy delivery due to less efficient operation of the generator plant. Fuel savings is about the only benefit of the solar power—it doesn't save any other utility operating costs. Once a large number of buildings on a utility circuit install large solar energy systems, there is no more load on that circuit to use additional solar power, and the solar generation may need to be curtailed. For example, Hawaii limits solar generation to 15 percent (up from previous 10 percent) of the peak load on a utility circuit without a special study

Interview with Solar Advocate Renee Azerbegi

Renee Azerbegi (Figure 1-9) was president of the Colorado Renewable Energy Society at a time when the state's constitution was amended to require a renewable energy standard with an amount set aside for solar energy in particular. She earned a bachelor of science in environmental science and geography from University of California at Berkeley and a master's in engineering from University of Colorado. She is now president of Ambient Energy Inc., a company providing energy modeling, sustainability ratings, and professional services for buildings.

Figure 1-9. Reneé Azerbegi was president of the Colorado Renewable Energy Society when the state's constitution was amended to require utility companies to utilize solar energy. (Photo by the author.)

What is a Renewable Energy Portfolio Standard?

It's a requirement that the power producers in a state use at least some fraction of renewable energy. Under Amendment 37, which passed in 2004, the state's largest electricity providers were to obtain 10 percent of their power from renewable energy resources by 2015, with 4 percent of this coming from solar electric sources. The measure also required qualifying utilities to offer customers a minimum rebate of $2 per watt for solar electric generation, provided incentives for utilities to invest in renewable energy resources that provide net economic benefits to customers, and limited the retail rate impact of renewable energy resources to 1 percent of the total electric bill annually for each customer of a qualified retail utility. This measure plus the federal solar tax credits jump-started Colorado's solar power industry. More recently the requirement was raised to 20 percent renewable energy by the year 2020.

How were you involved in Colorado's renewable energy portfolio standard?

I was president of the Colorado Renewable Energy Society (CRES) in 2004 when Amendment 37 passed. CRES played a major role in supporting Amendment 37. The authors of Amendment 37 included lawyer Ron Lehr, representing CRES, and lawyer Rick Gilliam, representing Western Resource Advocates, and others.

What do you mean by "Amendment 37"?

Colorado is unusual among states because it is possible for citizens to sign a petition to put an amendment on the ballot, and amend the state's constitution if it is passed by a vote of the people. Amendment 37 is a ballot issue that voters approved in 2004 to establish a renewable energy standard for the State of Colorado.

Why was the passage of Amendment 37 unique?

This was the first voter-backed renewable energy measure with a solar set-aside (a specific goal for solar energy)] in the United States.

Why did you have to do a constitutional amendment—aren't there easier ways to change the law?

Despite the best efforts of a few legislators from both political parties who introduced bills, and despite constituents telling them they wanted solar power, the Colorado state legislature voted down standards in three separate attempts in three years. Inexplicable. Coloradoans want cleaner air and more renewable energy jobs. So we took it to the people in the form of a constitutional amendment. It was a hard-fought campaign. The utility company spent over a million dollars on television advertisements which included menacing black clouds and thunder and lightning. The solar energy industry contributed about $70,000, and the wind industry contributed about $45,000 to promote the measure. A lot of the advocacy of the measure was grass-roots. We weren't downtown [Denver] the night the ballot measure passed, and the level of excitement was awesome. It became Amendment 37 to the Constitution of the State of Colorado.

You must have made enemies in the legislature by going around them to their boss—the people.

On the contrary, we found a lot of new friends in the legislature. In March 2007, the Colorado legislature adopted and the governor signed HB 1281, which increased the renewable energy requirement to 20 percent by 2020 for investor-owned utilities, and increased the number of utilities involved by including all rural electric cooperatives.

documenting the impacts of the solar generation on the local circuit and the larger utility system. Net metering also introduces a socioeconomic problem because it foists more of the cost of operating the utility on those least able to afford it—rich people install enough solar to bring their utility bill to zero, yet still use the utility power on a daily basis under a net-metering arrangement. Those unable to afford an expensive solar energy system are saddled with a higher bill.

So we understand net metering to be an incentive offered by utilities for solar energy systems at the expense of other ratepayers. In addition to this economic reason there are also technical reasons why not everyone can net-meter. Thus net metering is not the long-term solution for integrating large amounts of intermittent solar energy resources onto the utility system. In order to ease the economic constraints to net metering, there are several cost-recovery measures that a utility could take, including a "wholesale" or "buy-back" rate (c/kWh) that is lower than the retail rate for power. In other words, the utility may sell power according to their rate schedule but pay for power put back on their system at only the "avoided cost" that they actually save as a result of the solar power. The utility may also charge "stand-by charges" ($/kW/month) to pay for the utility infrastructure (distribution, transmission, generation, spinning reserve) that supports your building regardless of your solar generation.

Technically, net energy metering solves the *thermodynamics* problem of where energy (kWh) comes from and where it ends up, but not the *transport phenomenon* concerning volts, amps, frequency and waveform delivered where and precisely when. These details are the topic of the next section.

Predicting and Achieving Utility Cost Savings (Performance Simulation)

It is easy to overestimate the utility cost savings associated with a solar energy system. First, the system must be configured to physically save energy. For example, a solar water heating system must be configured to heat the cold water coming in before it mixes with water that has already been heated by conventional fuels. Then, the actual effect of this energy delivery on the cost of operating the energy system must be evaluated. It is not possible to put a value on the energy delivered by a solar energy system without considering the entirety of the utility bill and the details of the applicable utility rate schedule. In order to calculate the energy cost savings of a solar energy system it is necessary to calculate the utility bill with and without the contribution of the solar energy system.

Time-series simulation is often used to predict the energy delivery of a solar energy system under changing conditions (sunlight, temperature). In time-series simulation, the state of the system and associated energy delivery are calculated in the first time-step, and the results of that calculation become the initial conditions for the next time-step. By sequencing through all the time-steps in an analysis period, an integration of the power quantities (kW) over time (hours) gives the energy savings (kWh) and cost savings ($/month, $/year) associated with a solar energy project. Most computer programs use time-steps of one hour and an analysis period of one year, so they perform energy balance calculations for each of the 8,760 hours in a year (24 hours/day*365 days/year). Some accuracy is achieved by doing the solar analysis in small time-steps such as hourly. Solar resource information, such as that in Typical Meteorological Year (TMY) weather files, reports solar energy incident on a surface in an hour, in units of kWh/hour. A typical value for this data in an hour may be 500 Wh/m^2/h, for example. Three alternative interpretations of that value are presented here:

(a) Most hourly simulation programs (HOMER, SAM, TRNSYS, each to be discussed later in the chapter) interpret this to be mean a power of 500 W/m^2 incident for the full hour, as illustrated in Figure 1-10a. This would accurately state the condition under overcast sky, when the solar radiation is not changing with time. It would also represent effect of the angle at which the sunlight would hit the surface of a solar collector that was in a fixed position, which would not change by much over the hour.

(b) A second approach interprets the energy in an hour as a specified power level of a solar energy system (the rated power level, kW, associated with full sun) and a fraction of the time (hours) that the system delivers this power, so a value of 500 Wh/m^2/h from the weather data would be interpreted as 1,000 W/m^2 for only half of the hour, such as shown in Figure 1-10b. This method, used in the REO computer program (Walker 2009a), is convenient because solar energy products are rated considering a solar intensity of 1,000 W/m^2. This method would be accurate under partly cloudy conditions, when a solar collector is either in full sun or fully

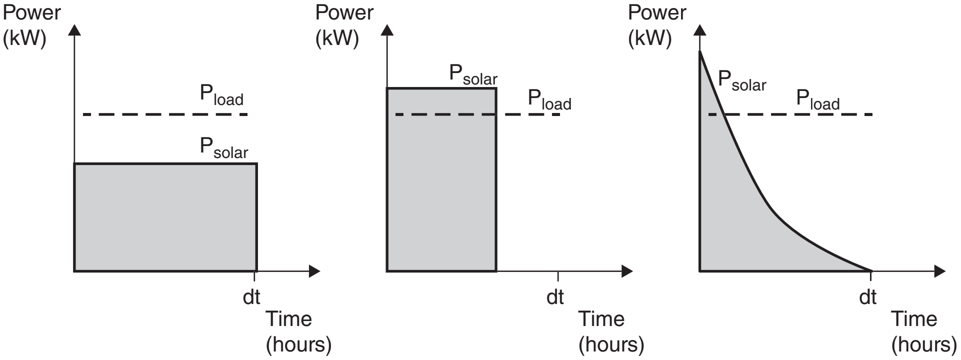


Figure 1-10. Three alternative ways of considering the same energy delivery (kWh) within a time-step: **(a)** solar power is constant over the full time step; **(b)** solar power is at a rated value for a fraction of the time step; and **(c)** solar power varies as the distribution of Equation 1-6 within the time step. (Figure by the author)

shaded by a cloud. It would also represent solar collectors that track the sun as it moves across the sky. The reason we are limited to these two alternatives is that we only have one number as input: the amount of solar energy in the hour (in kWh/m^2/hour). So we can solve for only one unknown, which is the power level (kW) in the first alternative or the fraction of time (hours) in the second alternative.

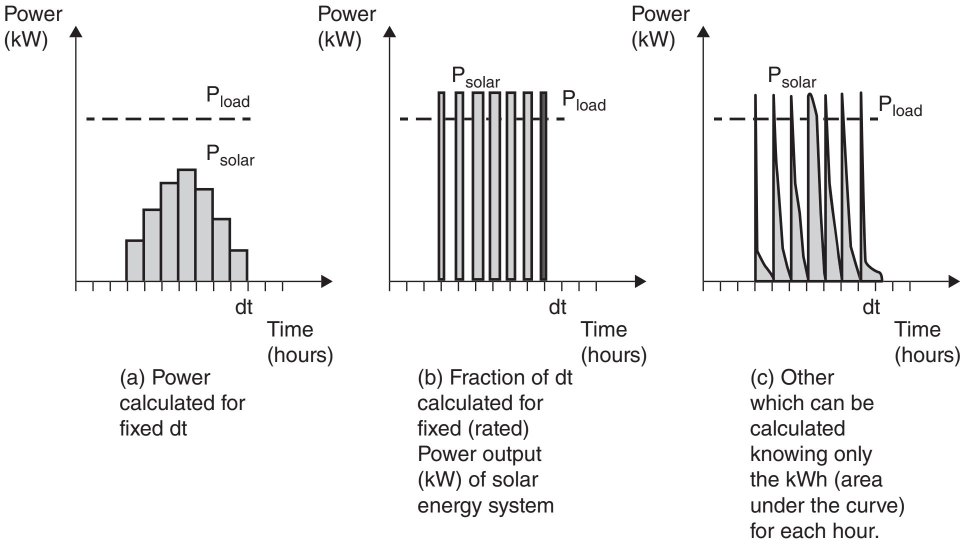
(c) A third alternative is to use a distribution, as shown in Figure 1-10c. Since we only have one equation (the kWh for the hour), our distribution must also involve only one unknown. The value of the actual power output of a solar energy system, P_{solar} (kW), depends on the underlying solar resource at location and may be displayed as a "duration curve" which show the value of the power output of a solar system of rated size P_{rated} (kW) over a time period T (hours). P_{rated} may be thought of at this point as the maximum output under full-sun, but will have more specific definitions in subsequent chapters. An equation that agrees very well with empirical duration curves for how power, P_{solar}, varies over the time period T, is given by the distribution

$$P_{\text{solar}} = P_{\text{rated}}\,(1 - (t/T)^n) \tag{1-6}$$

Where t/T is the fraction of time through the time period, from a minimum of $t/T = 0$ to a maximum of $t/T = 1$. For solar energy generators that are powered by sunlight, only the 4,380 daytime hours in a year are included and $T = 4380$. Conservation of energy (First Law of Thermodynamics) requires that the coefficient $n = \text{CF}/(1\text{-CF})$, where CF is the "capacity factor" for a given location. The capacity factor is derived from solar or wind resource data at a location and is reported in the resource databases described in Chapter 2 of this book. To relate this to the 500 Wh/m^2/h resource number that we used as an example above, 500 Wh/m^2/h would equate to a capacity factor of 0.5 if the rated power level, or "capacity" is associated with full sun at 1000 Wh/m^2/h. All three figures 1-10a, 1-10b and 1-10c have the same value of the capacity factor, and it is illustrated as the area under the curve divided by the whole area of the diagram. In 1-10a capacity factor is the fraction of the rated capacity for the hour; in 1-10b it is the fraction of the hour at rated capacity; and in 1-10c it is a distribution which splits the difference between these extremes.

The area (kWh) under all three of the curves of Figure 1-10 is the same, but the curves bear some important differences—in (a) the solar energy is used fully on-site, as the solar power never exceeds the load; in (b) solar energy is generated in excess of the load for part of the time-step, but not generated for the remainder of the time-step; and in (c) the distribution splits the difference between these two extremes, with the solar power exceeding the load for a small fraction of the time-step. Power in excess of the load could be sold back to the utility, could be saved in batteries, or could be wasted. Thus, while the three alternative ways of looking at the curve of kW versus hours within a time step all yield the same delivery of solar energy (kWh), they may have different operational effects and utility cost savings associated with them. The first assumption of constant power within each timestep is suitable only for short timesteps as is used in all of the hourly simulation programs currently available. The second method of assuming fixed power for a calculated fraction of the time-step provides acceptable accuracy at longer time-steps and has been used for time periods as long as one-half day in the REO computer program. The third method of using the distribution maintains accuracy with timesteps up to a full year under some circumstances, and then $T = 8760$ hours where 8760 is the number of hours of a single year.

Figure 1-11 shows what an hourly simulation would look like for a 12-hour day using each of the three alternative treatments



(a) Power calculated for fixed dt

(b) Fraction of dt calculated for fixed (rated) Power output (kW) of solar energy system

(c) Other which can be calculated knowing only the kWh (area under the curve) for each hour.

Figure 1-11. Construction of an hourly simulation for one day showing alternative assumptions: **(a)** calculated power level for fixed time; **(b)** calculated fraction of time for fixed power level; and **(c)** a distribution with the same area (same kWh) as the first two. (Figure by the author) of Figure 1-10. In each case, what we know is the kWh/m^2/hour of incident solar power for an hour, and then we infer either: (a) a calculated power level for the fixed period of time dt (one hour); (b) a calculated fraction of time for a fixed power level (rated kW); or (c) a distribution which also has only one variable. All three of these profiles accumulate the same number of kWh in the day.

Once the power serving the on-site load (P_{load} or P_{solar}, whichever is less) and the power sold back to the utility or put into a storage battery ($P_{\text{solar}} - P_{\text{load}}$) are ascertained by assuming one of the profiles of Figure 1-10, we may integrate from time-step to time-step over the duration of the analysis period (usually hourly simulation for one year, 8,760 hours) to calculate total energy purchased from the utility:

$$E_{\text{from utility}} = \int_0^{8760} Max(0,(P_{\text{load}} - P_{\text{solar}}))\,dt \tag{1-7}$$

And total excess energy sold back to the utility over the analysis period

$$E_{\text{to utility}} = \int_0^{8760} Max(0,(P_{\text{solar}} - P_{\text{load}}))\,dt \tag{1-8}$$

Where P_{load} is the rate at which power is consumed on-site (kW), on the customer side of the utility meter. The utility cost savings or revenues associated with each of these would have to be integrated, similarly over the 8,760-hour year, by calculating the utility bill with and without solar energy, using the details of the utility rate schedule.

The time period T is arbitrary, but needs to be small if we assume a constant output power from the solar system. If we assume the distribution profile (c in Figure 1-10), then we can maintain an acceptable accuracy at time periods up to one year. Here assume the time period T to include only the 4380 daytime hours of the year- then power purchased at night must be calculated separately and added to this to the total to account for all of the power purchased from the utility. The load, P_{load} (power requirement), is taken to be constant, limiting the application of this simplification to those with constant demand. Substitution of Equation 1-6 into 1-8 and integrating gives an equation for energy sold back to the utility

$$\begin{aligned} E_{\text{to utility}} &= (P_{\text{rated}} - P_{\text{load}})Te^{(ln(1-\frac{P_{\text{load}}}{P_{\text{rated}}})/n)} \\ &- \frac{P_{\text{rated}}}{T^n(n+1)}(Te^{(ln(1-\frac{P_{\text{load}}}{P_{\text{rated}}})/n)})^{(n+1)} \end{aligned} \tag{1-9}$$

And substitution of 1-6 into equation 1-7 and integrating gives the expression for energy purchased from the utility when solar is insufficient to meet the load.

$$\begin{aligned} E_{\text{from utility}} &= (P_{\text{load}} - P_{\text{rated}})T + \frac{P_{\text{rated}}T^{(n+1)}}{(n+1)} \\ &- (P_{\text{load}} - P_{\text{rated}})t_{lm} - \frac{P_{\text{rated}}t_{lm}^{(n+1)}}{(n+1)T^n} \end{aligned} \tag{1-10}$$

TIP

Calculating Cost Savings: Utility-Bill Analysis

Many hand calculations and computer programs multiply calculated solar energy delivery (kWh) by a value for delivered solar power ($/kWh) in order to calculate utility cost savings ($). But that is fundamentally incorrect and there is only one way to calculate utility cost savings associated with a solar project: calculate the utility bill **with** and **without** solar using the same calculation that the utility would use to calculate your bill. Utility rate schedules are often complicated, involving time-of-day, seasonal rates, demand rates ($/kW peak demand), and block rates ($/kWh for the first block of kWh, then less). The value of the solar energy delivery can be evaluated only in the context of the overall utility bill for a building.

In Equation 1-10, t_{lm} is the time period that P_{solar} exceeds P_{load}, and is found by setting P_{solar} equal to P_{load} in Equation 1-6 $t_{lm} = T(1 - P_{\text{load}}/P_{\text{rated}})$^(1/n).

Optimizing the Size of a Solar System

So we see that the economic returns diminish as we satisfy larger fractions of the energy demand with solar, and it is rarely cost effective to meet 100 percent of a load with solar. Solar systems are too often sized with only a "sweet spot" in mind, such as meeting the daytime demand (kW), meeting the average daily load (kWh/day), or a size that maximizes an available incentive payment. A more careful approach to sizing and design of a solar system would be to use optimization techniques to determine the size that minimizes life cycle cost while still meeting all the design criteria and constraints of a site. The objective is to minimize life cycle cost; the variables are design parameters such as solar collector area, battery or thermal storage volume; and constraints customize the problem for the situation including such things as maximum budget, maximum available roof area, and goal of some minimum fraction of energy use from solar. For an example of optimizing four design parameters of a residential solar water heating system (solar collector area, storage tank volume, heat exchanger area, and circulating fluid volume) to minimize life cycle cost see (Walker, 1991). Optimization techniques that have been used to size solar energy systems include calculus, linear programming and non-linear search techniques.

OPTIMIZATION USING CALCULUS (DERIVATIVE EQUAL TO ZERO)

This approach uses analytical methods (fundamental theorem of calculus) rather than numerical methods to determine the size (capacity, kW) of a renewable energy generator, P_{rated} (kW), that minimizes life cycle cost. We seek the value of P_{rated} that satisfies that condition:

$$\frac{dLCC}{dP_{\text{rated}}} = 0 \tag{1-11}$$

Utility energy cost savings are most often evaluated by time series simulation using a computer, but we can proceed with a simple hand calculation by assuming a very simple utility rate schedule consisting only of two rates: c_{retail} = retail cost of utility electricity paid for energy from the utility ($/kWh); and $c_{wholesale}$ = wholesale price received for electricity sold back to the utility. Life cycle cost is the sum of initial cost, $C_{initial}$ ($/kW) times P_{rated}, plus the present value of operation and maintenance costs and the present value of costs involved with purchasing power from the utility company and revenue from the sale of excess electricity back to the utility

$$\begin{aligned} LCC = {} & C_{initial}P_{rated} + C_{O\&M}P_{rated}PWF \\ & + C_{ratial}E_{from\ utility}PWF - C_{wholesale}E_{to\ utility}\ PWF \end{aligned} \tag{1-12}$$

Where $C_{O\&M}$ ($/kW/year) is the cost to operate and maintain the system per-year, per kW of rated capacity. Substitution of equations 1-9 and 1-10 into 1-12 and taking the derivative with respect to P_{rated} produces the expression that will be set to zero to ascertain the optimal value of P_{rated} that minimizes life cycle cost.

$$\begin{aligned} & \frac{dLCC}{dP_{rated}} = 0 = (C_{pv} + (C_{O\&M}*pwf) + (c_{retial}*pwf*((T*(-1 + \\ & ((1+n)\wedge(-1)) + EXP((LN((1-(P_{load}/P_{rated})))/n)))) - \\ & ((P_{load}-P_{rated})*T*((((1-(P_{load}/P_{rated}))*n)\wedge(-1))*P_{load}*(P_{rated}\wedge \\ & (-2))*(EXP(LN((1-(P_{load}/P_{rated})))/n)))) - ((T\wedge(-n))/(1+n)* \\ & ((T*EXP((LN((1-(P_{load}/P_{rated})))/n)))\wedge(1+n))) - (P_{rated}* \\ & (T\wedge(1-n))*((T*EXP((LN((1-(P_{load}/P_{rated})))/n)))\wedge n)* \\ & (((1-(P_{load}/P_{rated}))*n)\wedge(-1))*P_{load}*(P_{rated}\wedge(-2))*(EXP(LN \\ & ((1-(P_{load}/P_{rated})))/n)))))) - (cwhsl*PWF*((T*EXP((LN((1- \\ & (P_{load}/P_{rated})))/n))) + ((P_{rated}-P_{load})*T*((((1-(P_{load}/P_{rated}))*n)\wedge \\ & (-1))*P_{load}*(P_{rated}\wedge(-2)*(EXP(LN((1-(P_{load}/P_{rated})))/n)))) - ((T\wedge \\ & (-n))/(1+n)*((T*EXP((LN((1-(P_{load}/P_{rated})))/n)))\wedge(1+n))) - \\ & (P_{rated}*(T\wedge(1-n))*((T*EXP((LN((1-(P_{load}/P_{rated})))/n)))\wedge n)* \\ & (((1-(P_{load}/P_{rated}))*n)\wedge(-1))*P_{load}*(P_{rated}\wedge(-2)*(EXP(LN((1- \\ & (P_{load}/P_{rated})))/n))))))))) \end{aligned} \tag{1-13}$$

This is a transcendental equation, which means that the variable P_{rated} appears both in exponential terms and as a product multiplied by the exponential term, and may be solved by iteration (guess a value of P_{rated} and check to see if the equation equals zero, if not guess a higher or lower value), or software products, such as the "goal seek" function in Microsoft Excel spreadsheet may solve for P_{rated}.

Example Calculation of Optimal Solar System Size

Here we consider a constant load of 3 kW in Athens, Georgia (Table 1.1). The solar resource experts tell us that the capacity factor for solar photovoltaics feeding power to the utility grid is CF = 0.35 based on daylight hours (T=4380 hours). The utility charges $0.12/kWh for every kWh provided and pays $0.06/kWh for every kWh put back onto the utility system by the PV system. The cost of PV is taken at C_{pv} = $4.00 per Watt, but minus a 30 percent tax credit resulting in $2.70/W. Maintenance costs, $C_{O\&M}$ for this simple grid connected system without batteries is taken at $8.50 per kW per year. The present worth factor of 22 years corresponds to a 5 percent discount rate and a 4 percent inflation rate for 25 years. Equation 1-13 is typed into a cell of a Microsoft Excel spreadsheet and solved using the "iteration" feature of Excel. The optimal size of the system is found to be P_{rated} = 6.5 kW. From this we can calculate the initial and maintenance costs as well as utility costs and life cycle cost.

TABLE-1. EXAMPLE OF DETERMINING THE SIZE OF A PV SYSTEM USING CALCULUS OPTIMIZATION TECHNIQUES.

Site	Athens GA
Load, P_{load} (kW)	3
C_{pv} ($/kW)	$2,670
$C_{o\&m}$ ($/kW/year)	$8.50
PWF (years)	22.03
c_{retail} ($/kWh)	$0.12
$c_{wholesale}$ ($/kWh)	$0.06
CF	0.35
T, Time period (hours)	4380
Total Hours per year	8760
n, Equation 1-6	0.54
P_{rated} (kW), Equation 1-13	6.52
Energy to Utility (kWh) Equation 1-9	1,714
Energy from Utility (kWh) Equation 1-10 (*T* = daytime hours only)	4,865
Total load, L*8760 hours (kWh)	26,280
Life cycle cost Equation 1-12	$63,950

OPTIMIZATION USING LINEAR PROGRAMMING

Linear programming refers to computer programs which solve a system of simultaneous equations to explicitly calculate the optimal solution. The objective function of life cycle cost and each of the constraints are written as linear equations of the design variables to be optimized. This requirement is accommodated by making curved dependencies piecewise linear. For example, a curve of cost versus size might be approximated by three straight-line segments. Governing equations (such as conservation of energy) are coded as constraints that must be satisfied within the system of linear equations. These equations result in three matrices: one for the coefficients associated with each of the design variables; a second for the design variables themselves; and a third for the values of the objective function. Matrix inversion or iteration is used to solve for the matrix of the design variables that minimizes life cycle cost and satisfies all the constraints. Branching logic of multiple solutions accommodates binary variables that are not linear (solves the linear algebra problem for each possible permutation of the other variables that have binary or discrete values). Researchers at NREL have used this approach in the REOpt computer program to provide a recommendation for sizes of different renewable energy technologies (solar, wind, biomass, and so on) for a given load and conditions (NREL 2013).

OPTIMIZATION USING NONLINEAR SEARCH TECHNIQUES

If I formulate the solar design problem as it naturally comes to me, it involves a lot of non-linear, non-smooth, and discontinuous functions in the calculation of life cycle cost, so linear programming techniques are hard to implement and abstract. Many search techniques have been devised to try to find an optimal value among non-linear equations. Three that I have experience with are exhaustive search, gradient-reduction method, and evolutionary method. Exhaustive search refers simply evaluating all the possible sizes of a system or component to determine the value that minimizes life cycle cost. The HOMER computer program takes this approach by evaluating all the possible permutations of component sizes that the user specifies. Gradient reduction method refers to calculation of a derivative, but unlike the calculus method described above which explicitly calculates the optimal size in closed form equation, the gradient descent method uses the gradient (derivative in multiple dimensions) to inform a better solution and iterates until convergence criteria are satisfied. Evolutionary search technique has usefulness in my opinion because it can be set to try a very large number of solutions across the entire domain of the search, thus finding close to the optimum. It tries different combinations of variables in solutions that improve until convergence criteria are met. An example of convergence criteria is that the life cycle cost changes by less than 1 dollar in 5 sequential iterations. None of these search techniques is perfect. They all have advantages and disadvantages in certain applications. Non-linear optimization is not for the faint of heart. I often use the evolutionary algorithm to find a near-optimum solution, and then the gradient descent algorithm to make the recommended solar system size more exact. Both of these methods are available as free add-ins to the Microsoft Excel spreadsheet program and they are also sold as separate programs (for example: Premium Solver by Frontline Systems www.solver.com). The Renewable Energy Optimization (REO) spreadsheet computer program has used these optimization techniques to recommend solar system sizes that minimize life cycle cost for dozens of facilities including manufacturing plants and military bases (Walker 2009a).

Strategies for Maximizing Integration of Solar Energy with Conventional Utilities

Operational measures and changes to existing electrical and fuels systems will be needed in order to accommodate increasing amounts of intermittent and distributed solar energy. Following are strategies to incorporate more solar energy into the conventional utility energy system.

ACCOMMODATE A TWO-WAY FLOW OF ELECTRICITY AND INFORMATION

The existing utility transmission and distribution system was designed to distribute power from central power plants to users. The system involves loops, or more than one electric circuit to a facility, so the utility circuits are equipped with "network protectors" that prevent a flow of electric power in the reverse direction, which might be indicative of a fault (if power comes back it thinks it has a fault with another utility circuit). With distributed generation, the system must be modified to allow power to flow both ways: from the utility to energy consuming systems of a building and from the rooftop solar system back into the utility. There would also have to be a two-way flow of information and control. This will require much more automated data processing and active controls than today's rather inert system.

RECONFIGURE UTILITY CIRCUITS

Utility circuits may have to be reconfigured to allow excess solar generation on one utility circuit to be used on another circuit. This will involve additional switchgear and legs between circuits in utility substations. For example, a housing area with solar on every roof but very little electricity use during the day (parents at work; kids at school) would be configured to send power back through a substation and on to commercial or industrial loads during the day.

DEMAND RESPONSE

Demand response is the control of some loads, turning the load off or down if necessary. Demand response may be used to limit any sudden transitions in the load on the conventional system due to the intermittency of the solar resource. A noncritical load could be turned off when the solar energy is interrupted, and then turned back on again as a conventional generator's output is ramped up. This reduces the need for spinning reserve. An example would be cycling the heating elements of electric water heaters so that 25 percent of them are off at a time—the demand would be controlled but the energy would eventually be delivered and no one would even notice.

SPATIAL DIVERSITY

Solar energy systems spread around an area, such as a city, have a much steadier output than a single system all in one place, due to the scattered nature of clouds.

FORECASTING

Forecasting the output of solar power systems hours or days in advance based on weather forecasts, modeling, or sky observations can give advance notice that conventional generators will need to be started to make up for a drop in solar output due to approaching clouds. This advance notice reduces the requirement for spinning reserve.

DIVERSITY OF RESOURCES

It is a myth that there is one central solution that is best for all. Rather, a diversity of generation resources (solar, wind, fossil, hydro, etc.) is most robust. Overreliance on any one energy generation resource results in operational and economic problems and increases the risk of catastrophic failure.

TRACKING SOLAR COLLECTOR MOUNTS

Tracking mounts that follow the sun as it moves across the sky produce a steady output that does not fluctuate with sun angle. Moving the solar collector to face toward the sun provides essentially the same output from sunrise to sunset, removing one of the major sources of fluctuation in the solar resource (the other one being clouds).

ISOLATE CRITICAL CIRCUITS

Important loads that require a higher reliability may be isolated in order to serve them with available power first and exercise demand control over less important loads.

ENERGY STORAGE

A means to store solar energy, either as electrical battery or tank of heated fluid, and either at the location of the solar energy system or in a central location, would couple the intermittent solar energy delivery to the load. It is not feasible to store solar energy over from summer to winter, but it is quite possible to store enough solar energy to serve the load while a conventional generator is started (minutes) or to increase the output of a thermal power plant (hours) or to store solar energy for use overnight or even over a period of three to five days. Even a small amount of storage increases the value of the solar energy and smoothes the integrations with conventional systems substantially. Energy storage will be required in the grid of the future. Very short term storage (capacitors) controls voltage and power quality; storage of a few seconds (compressed air/hydraulic motor) could smooth transitions; storage of a few minutes (ultracapacitors, batteries) provides enough time to start or ramp up the power from other generators; storage of a few hours (batteries, flow batteries) enables peak-shifting, demand response, and storage of the intermittent renewable energy resource. Storage of end-use product is often more efficient that electric storage. Examples include storage of chilled water for cooling; hot water for heating; or pumping water for livestock into a tank only when the sun is shining. Storage of energy for days or from summer season to winter season would be very desirable for solar energy development, but lacks feasibility due to the scale of the storage—thus we may expect fossil fuel or nuclear to be in our energy mix for a very long time, but full use of solar energy can extend their supply and reduce their environmental impacts.

Example of Solar Storage

Sacramento Municipal Utility District (SMUD) initiated an 18-month trial on 42 homes in Rancho Cordova, California. The demonstration project provides each of 15 homes with one lithium ion (Li-ion) battery that is a 2-foot cube providing 3 hours average load, and costing $25,000 each. The project also installs three larger Li-ion batteries, each a 4-foot cube costing $75,000 to store energy for 27 more homes in groups of 9. Assistant General Manager for Power Supply and Grid Operations Paul Lau said “want to see what benefits SMUD gains from load-shifting and having the batteries and rooftop PV available to smooth out our load” (SMUD 2012).

Microgrids

Microgrid strategies provide the flexible configuration and control to operate a system regardless of the state of the utility or any individual generator. These strategies also provide the ability to transition between modes and respond to dynamic and transient events. Microgrid controls maintain required frequency and voltage levels; disconnect and seamlessly resynchronize with the grid; start with no utility power (“black start”); control loads by interfacing with system control and data acquisition (SCADA) and energy management and control systems (EMCS); and control of the output of generators, such as the solar energy systems. Microgrid research is not into any particular technology, but how various energy technologies may be integrated by smart controls.

The most important thing for now regarding integration of solar energy into the utility system is to involve the utility early in the planning of your solar energy project. The utility will study how the proposed project impacts reliability and integrity of the utility grid system. Backup and standby requirements imposed by utilities will probably increase with increased use of intermittent solar energy.

REFERENCES

Butti, Ken, and John Perlin. 1980. *Golden Thread: 2500 Years of Solar Architecture and Technology.* Palo Alto, CA: Cheshire Books.

Lissel, Lars, Tim Tetrault, and Andrea Watson. 2009. *Solar Ready Buildings Planning Guide.* Technical Report NREL/TP-7A2–46078. Golden, CO: National Renewable Energy Laboratory.

Mangano, Joseph J., and Janette D. Sherman. 2012. “An Unexpected Mortality Increase in the United States Follows Arrival of the Radioactive Plume from Fukushima: Is There a Correlation?” *International Journal of Health Services* 42:47–64.

NABCEP. 2011. *PV Technical Sales Job Task Analysis*. www.nabcep.org. (August 8). www.nabcep.org/wp-content/uploads/2011/08/NABCEP-PV-Technical-Sales-JTA-8-8-11-Web.pdf (accessed August 2, 2012).

Natural Resources Defense Council (NRDC). n.d. "Disaster in the Gulf."]www.nrdc.org/energy/gulfspill (accessed July 29, 2012).

NREL. 2013 *Upgrade to REopt Tool Means a More Robust Resource* http://www.nrel.gov/tech_deployment/news/ 2013/2073.html, Janurary 13, 2013; accessed March 20, 2013.

RS Means. 2006.*Green Building: Project Planning and Cost Estimating* (2nd ed.). Kingston, MA: Reed Construction Data.

Sacramento Municipal Utility District. 2012. "SMUD, Partners Kick-off Energy Storage Project" news release, June 29, 2012. https://www.smud.org/en/about-smud/news-media/news-releases/2012-06-29.htm (accessed July 29, 2012).

Stoltenberg, Blaise, and Eric Partyka. 2010. *Procuring Solar Energy: A Guide for Federal Facility Decision Makers*. DOE/GO-102010–3030, Office of Scientific and Technical Information. www.osti.gov/bridge. Oak Ridge, TN: US Dept of Energy.

US Energy Information Administration (USEIA). 2011. *International Energy Outlook 2011*. www.eia.gov/forecasts/ieo/pdf/0484%282011%29.pdf (accessed July 29, 2012).

Walker, Andy. 1991 "Thermodynamic Analysis and Economic Optimization of a Two -Phase Self-Pumping Solar Water Heater." Colorado State University, University Microfiche International Dissertation Information Service No. 5712.

——— 2009a. "An Heuristic Approach to Renewable Energy Optimization." ASME 2009; 3rd International Conference on Energy Sustainability, July 19–23, 2009, San Francisco, CA.

——— 2009b. "Tax Incentives for Renewable Energy." (August 19). www.govenergy.com/2009/pdfs/presentations/Financing-Session03-Walker_Andy.pdf (accessed August 3, 2012, no longer active link, contact author for copy).

Walker, Andy, Donna Heimiller, Alicen Kandt, and Anne Crawley. 2006. "Renewable Energy Screening: Identifying and Prioritizing Solar Opportunities in Federal Facilities." ASME/ASES Solar 2006. Denver, CO: American Society of Mechanical Engineers.

Walker, Andy, Greg Katz, David Mills, and Anne Grette Hestnes. 2003. *International Performance Measurement and Verification Protocol*. Vol. 3 of *Concepts and Practices for Determining Savings in Renewable Energy Technologies Applications.* Washington, DC: Department of Energy.

2

The Solar Energy Resource

The disc of the sun adorns many ancient monuments and temples, which should be no surprise—having the sun on your side would have been essential in agriculture, war, or almost any endeavor. The seasons and cycles of life derive from the changing position of the earth relative to that of the sun. In this chapter we describe how to calculate the power and timing of the solar energy resource available to the different types of solar energy conversion technologies: photovoltaics, solar water heating, solar air heating, and windows of buildings. "Power" from the sun is energy per unit time (kW, Btu/hr), and often per unit area (kW/m^2, Btu/hr/ft^2). "Timing" refers to how this level varies with hour-of-day and day-of-year. This chapter will also describe the "quality" of sunlight related to its spectral nature. Hopefully, this piques a persistent awareness of where the sun is in the sky at what time of day and what time of year, and the effect of latitude. This chapter also discusses sources of measured data regarding the solar resource; software to analyze solar position or intensity for various solar energy applications; and applications for solar resource data such as forecasting output and diagnostics of existing systems.

Dave Renné, previously of NREL and now a consultant, has been a great help in understanding how to get and to use available solar resource data and how to interpret the indicators of data quality. An introduction to all aspects of solar resource assessment is described in (Renneet al. 2008).

STRUCTURE OF THE SUN

The structure of the sun has not been observed, but rather inferred from theory and is described in terms of layers (Chen 2011). The boundaries between layers are gradual rather than distinct. Figure 2-1 is a conceptual diagram of the layers of the sun and not to scale, and showing that boundaries between layers are not well defined.

Core

The core of the sun consists of a plasma of nuclei and dissociated electrons at a temperature of 15 million degrees Kelvin. Density in the core is on the order of 100 g/cm^3, and the core contains 50 percent of the mass of the sun in 7 percent of the sun's volume. All of the energy of the sun is generated by fusion in the core, within a maximum of about 100 million meters (3.28 million feet) radius, and it radiates out in form of gamma rays. The sun is burning its fuel rather slowly: the rate of heat generation per unit mass or per unit volume is thought to be less than many energy conversion processes on earth, about 276 W/m^3 at a maximum in the center, but there are a lot of m^3 in the core to multiply that by.

Radiative Zone

The gamma rays from nuclear fusion propagate slowly through the radiative zone by a process of absorption and reemission. The radiative zone has a density that reduces from 5 g/cm^3 at the interior to 1 g/cm^3 and is a temperature of around 4 million K.

Convection Zone

As the gases get less dense, convection becomes more efficient than radiation to propagate heat away from the core and convective cells develop, giving the brightness of the sun a granular appearance. The convective zone consists of hot gas in motion. The density is less than 1 g/cm^3.

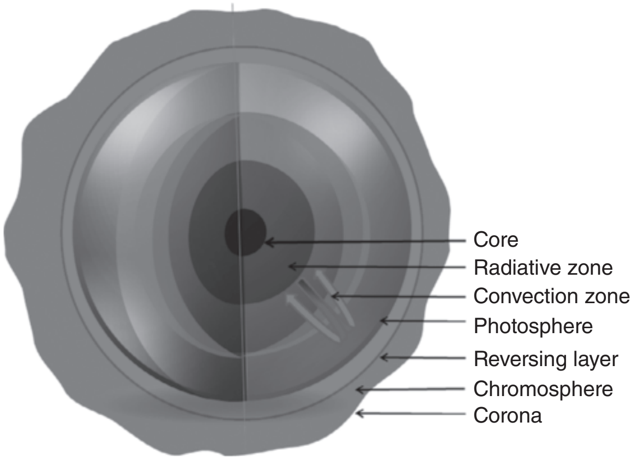


Figure 2-1. Outer layers of the sun act as a containment vessel for the nuclear fusion in the core. The visible part of the sun is the photosphere, which radiates the spectrum of light that we receive on earth. (Figure by the author; not to scale.)

Photosphere

The photosphere is a plasma of ionized hydrogen and helium. The density is less than 0.001 g/cm^3. The photosphere is the visible surface of the sun. Although the nuclear reactions in the sun emit radiation at discrete wavelengths, the photosphere absorbs all the radiation coming from the inner layers of the sun and emits it with a spectral distribution similar to that of a blackbody at 5,800 K. This is because the photosphere consists of ionized gas that can be in a very large number of energy states and so can absorb many different wavelengths and reemit radiations of many wavelengths—almost, but not exactly, the same as Plank's distribution for a blackbody radiator. The photosphere is about 400 km thick.

Outer Layers

The outer layers are more transparent but are also visible with optical aids.

- Reversing layer: several hundred km thick
- Chromosphere: around 10,000 km thick. The temperature is about 7,000 K
- Corona: very low density, high temperature on the order of 1 million Kelvin. The corona is visible when the disc of the sun (the photosphere) is occluded by a disc shape or a lunar eclipse.

The end of the sun's radius is not well defined, with evidence of solar particles far out into the system of planets.

Because of this complex structure of the sun with radiation of different types emitted by the outer layers, the spectrum of radiant energy coming from the sun is not simply that of a blackbody at 5,800 K. Although that spectral distribution is often used to approximate sunlight, more detailed heuristic data is required to model the effect of the of the details of the solar spectrum on things such as photovoltaic devices, devices that interact very accurately with the wavelength of incident light.

The source of the sun's energy is fusion, but when I look at the structure of the sun, I see the important role that gravity plays. Gravity causes the radiative and convective layers to compress the reactants in the core and act as a containment vessel for the nuclear fusion.

NUCLEAR FUSION: THE SOURCE OF THE SUN'S POWER

Hans Albrecht Bethe won the Nobel Prize for his 1938 description of how the stars generate power based on nuclear fusion reactions (NobelPrize.org 2012). Bethe described different reactions for stars of different size, but in our sun, energy is generated by the fusion of hydrogen to produce helium. In fact, helium was named in honor of Helios, the mythological Greek god of the sun, by William Ramsey in 1896, when he noticed that the wavelengths of light coming from the sun did not match those emitted by any gas that he had tested up to that time, and thus must be associated with a newfound gas (LLNL 2007).

The nuclear reactions described by Bethe involved hydrogen nuclei (H), a particle called a deuteron (D), positrons (e^+), gamma rays (γ), neutrinos (ν), and helium nuclei. The reaction of Equation 2-1 shows two hydrogen nuclei coming together to form a deuteron and emitting a positron and neutrino (Chen 2011):

$$^1H + {}^1H \rightarrow {}^2D + e^+ + \nu + 0.164\ MeV \tag{2-1}$$

The next nuclear reaction in the sequence combines the deuteron with another hydrogen nucleus to form an isotope of helium.

$$^2D + {}^1H \rightarrow {}^3He + \gamma + 5.49\ MeV \tag{2-2}$$

And the third nuclear reaction combines two of these isotopes to produce the complete helium nuclei and release two more hydrogen nuclei.

$$^3He + {}^3He \rightarrow {}^4He + 2\ {}^1H + 12.85\ MeV \tag{2-3}$$

Energy is released in each of these reactions. Not all of the energy of Einstein's relation $E = mc^2$ is available to us as solar energy from these reactions, because the neutrinos carry undetected energy out of the sun. Considering that the reactions of Equations 2-1 and 2-2 must occur twice and that of Equation 2-3 once for each helium nucleus produced, the energy generated with each helium nucleus is 25.16 *MeV* (Chen 2011).

THE SPECTRAL NATURE OF SOLAR RADIATION

Before the understanding of quantum mechanics, people were puzzled by the nature of light. Some behavior was explained by light as a wave and other behavior explained by light as a particle, called a *photon*. Max Plank helped explain this dual nature of light. I think of a photon as a single wave of a specific wavelength, much like one could send a single ripple down a string.

Wavelegth and Frequency

A series of waves of wavelength λ (m), all of them traveling at a speed c (m/s), would pass a point at a frequency of ν (1/s) and:

$$\nu = \frac{c}{\lambda} \tag{2-4}$$

Energy of a Photon

Plank discovered the relationship between the frequency of a light wave and the energy content, ε of the photons,

$$\varepsilon = h\nu \tag{2-5}$$

Named in his honor is Plank's constant, *h*, a physical constant with a value of 6.6254×10^{-34} Joule-sec; or, in units more useful to us in this book, 4.13567×10^{-15} eV·s (Decher 1997).

ASTM Standard Solar Spectrum

The solar spectrum is closely approximated by the spectrum emitted by a blackbody at 5,762 K. The blackbody spectrum matches the solar spectrum almost exactly in the infrared portion of the spectrum but underestimates power in the visible portion and overestimates power in the ultraviolet portion. The solar spectrum has been standardized based on a series of measurements made in space outside the earth's atmosphere. Data are published as large tables with emissive power per unit area and per unit wavelength for each wavelength interval.

The standard spectrum outside of the atmosphere is shown in Figure 2-2, along with standard spectra with the effects of the atmosphere included. The term *AM0* refers to zero "air mass" outside the atmosphere. While the effects of clouds and precipitable water in the atmosphere varies with the weather, AM1 is the attenuation of solar energy caused by persistent constituents of the atmosphere measured perpendicular to the earth's surface. AM1.5 would be greater than one thickness of atmosphere and is representative of sunlight passing through the atmosphere at an angle. Ozone absorbs some ultraviolet and visible wavelengths and carbon dioxide and water vapor absorb many infrared wavelengths. The figure shows spectral power (W/m^2/μm) for the "extraterrestrial" case of no atmosphere (ASTM 2006) and also for global (both beam and diffuse) and direct and circumsolar with the effects of the atmosphere associated with a 37-degree tilt angle (ASTM 2008). *Circumsolar* means "around the sun" and refers to the forward-scattered light that is diffuse, but still coming nearly in the same direction as the direct beam radiation.

Approximately 7 percent of the power is in the ultraviolet portion of the solar spectrum with wavelength as short as 200 μm; 47 percent is in the visible range between 350 and 750 μm wavelength; and 46 percent is at longer wavelengths, as long as 2,500 μm in the infrared portion of the spectrum.

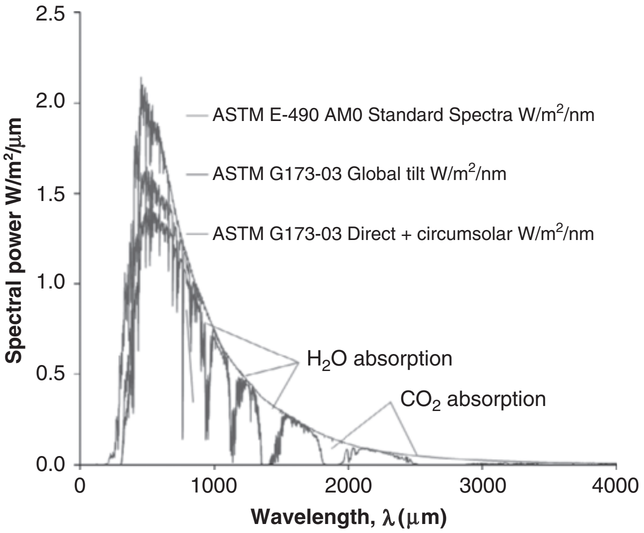


Figure 2-2. The standard spectral distribution of sunlight, published by ASTM, is important for determining performance of solar energy systems that depend on wavelength of the incident light, such as photovoltaics, selective surfaces on solar thermal collectors, and selective window glass. Illustrated here are the ASTM standards for spectral power as a function of wavelength for extraterrestrial (outside the atmosphere); global radiation on tilt = 37 degrees; and direct plus circumsolar radiation. (Figure by the author using data from ASTM 2008).

WARNING

Dangers of Ultraviolet Sunlight

Exposure to the energetic ultraviolet rays of sunlight is dangerous. Sunburn is dangerous due to complications of infection and interfering with important functions that skin performs. About 7,900 skin cancer deaths are attributed to overexposure to sun per year in the US (Davidson and Turkington 2012). Skin performs several important functions, and sunburn on a large enough portion of it can cause death by shock. Wear a long sleeve cotton or wool shirt with a collar when working in the sun, and a strong sunscreen if any time is to be spent outdoors. UV light also breaks chemical bonds, causing colors and flavors to fade and plastics to become brittle. Thus, glass coatings that filter out the UV would be recommended for windows used for daylighting or direct solar heat gain into an occupied space. But in the case of indirect gain such as a thermal storage wall or the cover glass of a solar collector, we would want the UV to penetrate the glass. Also in greenhouses, plants may need the short-wavelength ultraviolet light.

Concept

Implications of the Solar Spectrum on Photovoltaics, Window Glass, and Photosynthesis

The spectral nature of sunlight is important to photovoltaics because only photons with enough energy can create electron-hole pairs in the semiconductor material. A photon of sufficient energy (sufficiently high frequency, short wavelength) is absorbed and an amount of energy equal to the "band gap" of the semiconductor is imparted to an electron raising it from the valence band to the conduction band, thus creating the source of electric current from the PV device. The band gap depends on the material and on temperature. Energy of the photon in excess of the band-gap energy of a single electron is wasted, although using this excess energy to contribute to delivery of another electron is a strategy by which the efficiency of PV is being improved. Figure 2-3 shows the two parts of the solar spectrum that a PV device can't use.

Windows are often used to admit daylight, but on east and west orientations, and in warm climates, it is desirable to keep the solar heat out. About 47 percent of the power is in the visible part of the solar spectrum, and the peak spectral power is in that range. That should be no surprise since our eyes evolved in sunlight. So-called "selective" glass has coatings which absorb the infrared and ultraviolet portions of the solar spectrum, allowing the visible part to pass. Thus, as much as 53 percent of the solar heat could be kept out while still admitting most of the visible light and providing a clear appearance.

Discrete photochemical processes by which plants convert carbon dioxide in the air and water into glucose and other plant materials are actuated by wavelengths of light in the 400 to 500 μm range. It should be no surprise that the peak of the solar spectrum coincides with this requirement, since plants evolved in sunlight. Window glass in greenhouses would have to transmit these wavelengths efficiently.

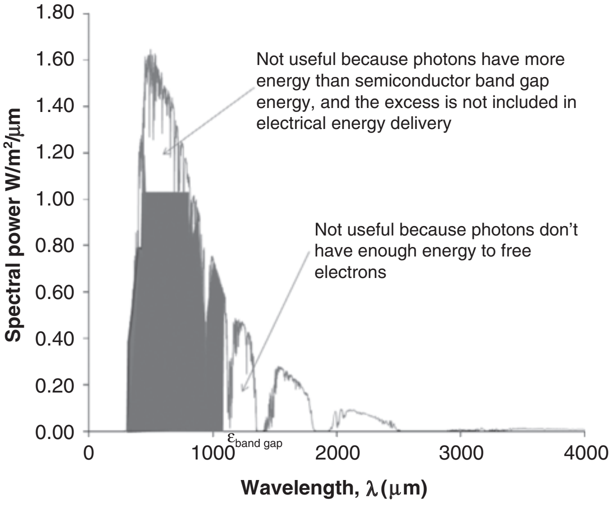


Figure 2-3. A photovoltaic device can only use the part of the solar spectrum with wavelength short enough, thus energy high enough, to create free electrons in the semiconductor material. Part of the solar spectrum with more energy than the band gap result in the extra energy being dissipated as heat. (Figure by the author)

POSITION OF THE SUN IN THE SKY

The position of the sun in the sky can be located accurately as a function of time-of-day and day-of-year (and of latitude). These calculations are used to evaluate alternative mounting positions for solar collectors and can be used to position a moving solar collector based on the calculated position of the sun. The Northern Cheyenne Tribal Capitol Building in Lame Deer, Montana, used solar position calculations to locate a window to illuminate the buffalo horn that the tribe used to carry fire from camp to camp. The Science and Technology Facility in Golden, Colorado, passes a tube through the roof to illuminate a dedication plaque in the floor on anniversaries. You can solve for the hour associated with a solar altitude angle of zero to tell your friends what time to meet at the trailhead at dawn. So it is possible to have a lot of fun with these equations.

Consider a spherical coordinate system where points are located by a *solar altitude* angle, measured up from the horizontal, and a *solar azimuth* angle, measured from the due-south direction. Figure 2-4 illustrates the definition of these angles, but before we provide the equations for these, we have to define all the parameters related to time of day and day of year.

Time-of-Year: Declination and the Seasons

The axis about which the earth rotates every 24 hours is tilted at an angle of 23.45 degrees with respect to the axis about which the earth revolves around the sun every 365 days. An angle called the *declination* varies between the two extremes: –23.45 on the winter solstice and +23.45 on the summer solstice. This angle is given the symbol δ and may be calculated for any other day of the year using

$$\delta = 23.45 \sin\left(\frac{360(n+284)}{365}\right) \qquad (2\text{-}6)$$

Where the units for the angles are in degrees and n is the number of the day of the year (for example, on January 1 $n = 1$, February 1 $n = 32$, and so forth to December 31 $n = 365$).

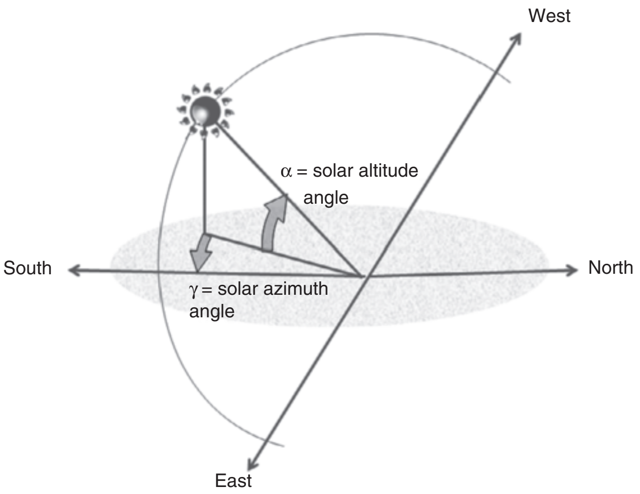


Figure 2-4. *Solar altitude angle* is angular displacement above the horizon, and *solar azimuth* is the horizontal angle from due south. (Figure by the author)

Figure 2-5 shows the position of the earth relative to the sun at different times of year. On the summer solstice, June 20 or 21, the northern hemisphere is tilted toward the sun and δ = 23.45 degrees. The North Pole (90 N latitude) is in the sun for 24 hours, as is the area of the Arctic Circle at 90 − 23.45 = 66.55 N latitude. So the Arctic Circle is where the sun shines 24 hours for at least one day a year (the summer solstice). Also, if you were at 23.45 N latitude, the sun would be directly overhead at noon on the summer solstice. This is the definition of the "tropics" between 23.45 N and −23.45 S latitude: there is at least one day per year (the summer solstice), when the sun is directly overhead at noon. At locations north of the Tropic of Cancer, the sun would appear lower in the sky. In Latin, *sol* means "sun" and *stice* means "stop," and the summer *solstice* is when the sun stops getting higher and starts getting lower in the sky each day. This day is celebrated as "midsummer" by the peoples of Europe, who thrust a pole into a hole in the ground and dance around it. At middle latitudes, say 40N, the sun is visible in the sky for about 15 hours per day on the summer solstice.

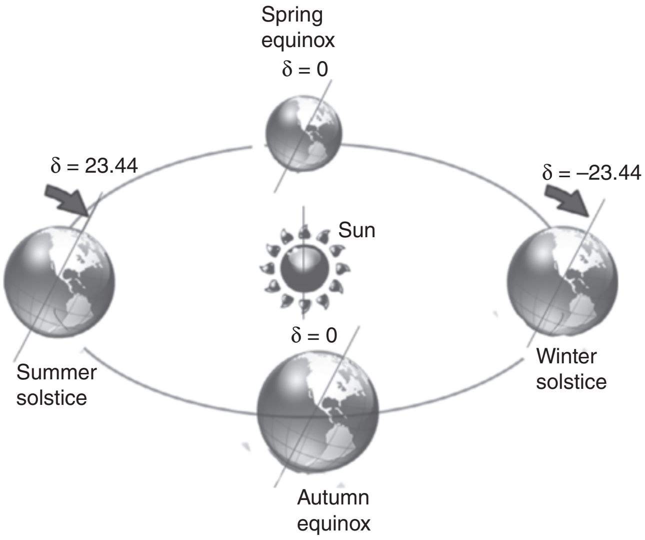


Figure 2-5. The *declination* is the angle of tilt between the earth's axis about which it rotates every 24 hours and the axis about which the earth revolves around the sun every 365 days. (Figure by the author)

On the winter solstice, December 21 or 22, the Northern Hemisphere of the earth is tilted away from the sun at declination δ = −23.45 degrees. On this day locations north of the Arctic Circle receives no sun, and the day is much shorter at middle latitudes, say nine hours at 40 N latitude.

On the spring equinox, March 20, the axis of daily rotation and the axis of annual revolution are orthogonal (sideways) to each other so the 23.45 degree tilt doesn't matter and δ = 0 degrees. The duration of the daytime is equal to that of the night, 12 hours, and thus the name *equinox*. The spring equinox is celebrated as Persian New Year in Iran.

Similarly, on the autumn equinox, September 22 or 23, the day and night are again of equal duration. On this day also δ = 0. If you were standing on the equator (latitude = 0), the sun would be directly overhead at noon on both the spring and autumn equinox.

Time-of-Day: Standard Time, Solar Time, and the Hour Angle

The earth rolls in sunlight at the rate of 360 degrees in 24 hours, or 15 degrees per hour. The *hour angle* is how far, in degrees, this rotation is away from solar noon, with east being negative and west being positive. The equation for hour angle is

$$\omega = \left(15\frac{\text{degrees}}{\text{hour}}\right)(\text{solar time} - 12) \tag{2-7}$$

With solar time on a 24-hour scale (so that 1 p.m. = 13:00), the sign convention will be observed. For example, at noon the hour angle is zero. At 11 a.m. it is −15 degrees, and at 1 p.m. it is +15 degrees. Standard time zones are a human invention not observed by the sun, so we must correct local standard time to solar time. There are 15 degrees of longitude per hourly time zone. The standard longitude, L_{std}, defining the Mountain Time Zone is 105 W. So to the east the longitude defining the Central Time Zone would be 90 W, and the Pacific Time Zone to the west would be defined by 120 W longitude. If your location, L_{loc}, falls exactly on one of these standard longitude lines then no correction required, otherwise solar time can be interpolated between time zones

$$\text{solar time (min)} = \text{standard time (min)} + \left(4\,\frac{\text{min}}{\text{degree}}\right)(L_{\text{std}} - L_{\text{loc}}) + E \qquad \text{(2-8)}$$

Where E is the value of the "equation of time." Its not only the earth and sun but also other planets tugging, too, and the equation of time is a correction that is determined empirically. The value of E varies from –15 minutes in February to +17 minutes in November. The equation of time is given by the equation (Beckman and Duffie 2006)

$$E = 229.2(0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B) \qquad \text{(2-9)}$$

Where the parameter B is $360(n - 1)/365$ and n is the number of the day of the year.

Another correction to remember is daylight savings time, which the sun does not observe, and requires subtracting an hour from "daylight savings time" to get "standard time" when daylight saving time is in effect (in summer). Not all jurisdictions observe daylight saving time.

Solar Altitude Angle, α (degrees)

The solar altitude angle, α, is the angular elevation of the sun above the horizon. The following derivations are from notes that I took during lectures delivered by Dr. Byron Winn, who led solar engineering at Colorado State University for many years. Consider a coordinate system with three unit vectors as illustrated in Figure 2-6.

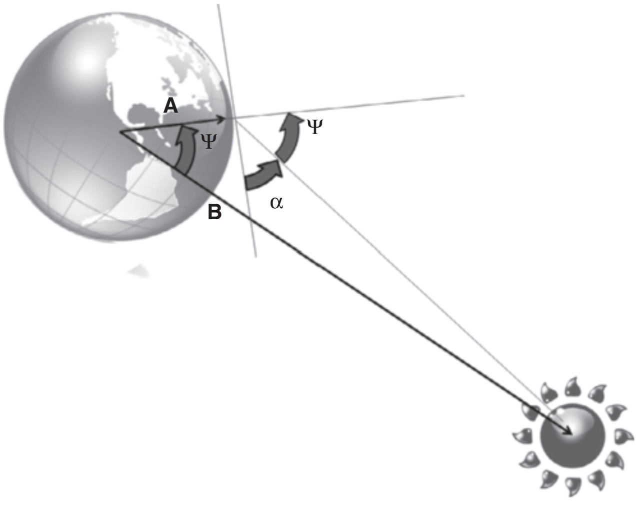


Figure 2-6. Vector A is to our location on earth; vector B is in the direction of the sun. The angle ψ is taken to be the same in both locations, since the sun is so far away and the rays are essentially parallel, and this approximation simplifies calculation of the solar altitude angle. (Figure by the author)

$\boldsymbol{i_x}$ is a direction from the center of the earth to a location on the equator (latitude = 0) with the same longitude as our location on the surface of the earth.

$\boldsymbol{i_y}$ is the perpendicular to $\boldsymbol{i_x}$ in the plane of the equator

$\boldsymbol{i_z}$ is in the direction of the North Pole from the center of the earth

Within this coordinate system identify the position of two vectors:

$\boldsymbol{A}$ is a vector from the center of the earth to our location on the surface of the earth

$\boldsymbol{B}$ is a vector from the center of the earth to the sun

In our coordinate system so defined, the position of the two vectors may be described in terms of latitude, declination, and hour angle.

$$\boldsymbol{A} = \cos\varphi i_x + 0 i_y + \sin\varphi i_z$$

and

$$\boldsymbol{B} = \cos\delta \cos\omega i_x + \cos\delta \sin\omega i_y + \sin\delta i_z$$

Figure 2-6 illustrates both vectors.

The dot product between the two vectors is evaluated

$$\boldsymbol{A} \cdot \boldsymbol{B} = \cos\varphi \cos\delta \cos\omega i_x + 0 i_y + \sin\varphi \sin\delta i_z \qquad \text{(2-10)}$$

The definition of "dot product" between two vectors is the magnitude of one vector times the magnitude of the second times the cosine of the angle between them.

$$\boldsymbol{A} \cdot \boldsymbol{B} = |A|\ |B| \cos\Psi \qquad \text{(2-11)}$$

As a simplification we assume that the angle labeled ψ in both locations of Figure 2-6 has the same value since the sun is so far away and the rays are essentially parallel.

$$\cos\Psi = \frac{A \cdot B}{|A|\,|B|} = \cos\varphi \cos\delta \cos\omega + \sin\varphi \sin\delta \qquad \text{(2-12)}$$

The angle ψ is $90 - \alpha$ in the figure, so $\cos\psi = \cos(90 - \alpha) = \sin\alpha$. Then

$$\sin\alpha = \cos\varphi \cos\delta \cos\omega + \sin\varphi \sin\delta \qquad \text{(2-13)}$$

Thus the altitude of the sun above the horizon is a trig function of latitude, declination (day-of-year as in Equation 2-6), and hour angle (time-of-day as in Equation 2-7).

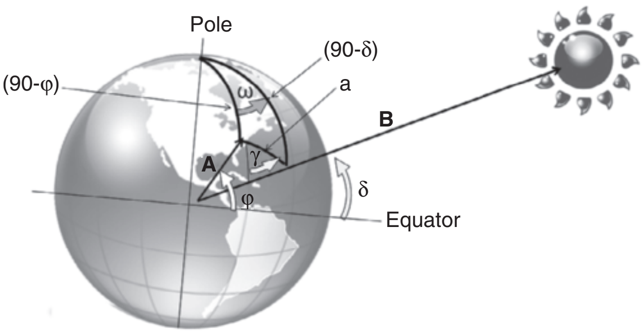


Figure 2-7. A spherical triangle identified by hour angle, latitude, and declination is used to solve for the solar azimuth angle (Figure by the author).

SOLAR AZIMUTH ANGLE, γ

Consider a spherical triangle drawn on the globe as illustrated in Figure 2-7. The top vertex of the triangle is the North Pole (or South Pole, if considering the reverse). A second vertex is the point at which we are located on the globe (our local longitude and latitude). And the third vertex is where a line from the center of the earth to the sun passes through the surface of the globe. As shown in the figure, vector A is from the center of the earth to our location and locates one of the vertices, and vector B is from the center of the earth to the sun and locates the third vertex.

A version of the law of cosines also holds in spherical geometry. The spherical triangle we are interested in is defined by the pole and the two other points on the unit sphere, and the arcs of great circles connecting those points ($90 - \delta$) and ($90 - \varphi$). Solving for the third arc, labeled "**a**" in the figure, will allow us to solve for the solar azimuth angle. The great circle arcs correspond to angles on the opposite sides, and the spherical law of cosines says that the following relationship holds (Wikipedia 2012):

$$\cos a = \cos(90 - \varphi)\cos(90 - \delta) + \sin(90 - \varphi)\sin(90 - \delta)\cos\omega \tag{2-14}$$

Simplifying this with the relation $\cos(90 - \varphi) = \sin\varphi$, we get

$$\cos a = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega \tag{2-15}$$

By comparison of this equation with the equation for solar altitude angle above, we recognize that $\cos a = \sin\alpha$. By another trigonometric identity: $\sin a = \sqrt{(1 - \cos^2 a)} = \sqrt{(1 - \sin^2\alpha)} = \cos\alpha$.

The great circle arc ($90 - \delta$) is subtended by the angle ($180 - \gamma$). We invoke the "law of sines," which is the same for a spherical geometry as it is in a flat plane, to make an equation that involves the solar azimuth angle γ.

$$\frac{\sin(90 - \delta)}{\sin(180 - \gamma)} = \frac{\sin a}{\sin\omega}$$

Again using the relation between sin and cosine

$$\frac{\cos\delta}{\sin\gamma} = \frac{\sin a}{\sin\omega}$$

And solving for the sin of the solar azimuth angle γ,

$$\sin\gamma = \frac{\cos\delta\sin\omega}{\sin\alpha} = \frac{\cos\delta\sin\omega}{\cos\alpha} \tag{2-16}$$

Equation 2-16 is an expression for the solar azimuth angle, the degrees of angle between due south and a horizontal line in the direction of the sun. The equation is a function of declination (day-of-year) and hour angle (time-of-day), but also of solar altitude angle, α, which is a function of these two parameters and also latitude as in Equation 2-13.

These two angles, equations 2-13 and 2-16, allow us to locate the position of the sun in the sky, how far off the horizon it is and how far east or west, as a function of time-of-day, day-of-year, and the latitude.

Concept

Implications of the Position of the Sun in the Sky on Solar Collector Placement, Building Floor Plan, and Window Orientation

The equations for solar altitude angle and solar azimuth angle have implications for solar energy system design. The path of the sun is from east to west across the sky each day, and on the spring and autumn equinox it rises directly east, cuts a high arc across the southern sky, but lower in the sky the higher the latitude, and sets in the west. On the summer solstice the sun rises a few degrees north of due east, passes almost directly overhead, and sets north of due west. In winter months, the sun cuts a lower arc across the southern sky (lower α). For locations in the southern hemisphere the directions would be reversed.

Surfaces facing toward the equator at a tilt equal to the local latitude maximizes annual energy delivery, tilting them back at a lower tilt angle increases summer delivery and tilting them up at a steeper angle maximizes winter delivery and makes delivery more uniform throughout the year.

The south vertical façade of the building will intercept the most sun on a winter day around noon. The east and west facades will receive maximum sun in the morning (east) and afternoon (west) in the summertime. Thus, general guidance is to stretch the floor plan of a building out from east to west, maximizing the southern exposure and minimizing the east and west exposures.

The area of windows on the east and west side of a building should be minimal and should have coatings to reduce solar heat gain in summer.

DIRECT BEAM, DIFFUSE, AND GLOBAL SOLAR INSOLATION IN THE PLANE OF A SOLAR COLLECTOR SURFACE

The amount of solar power available on a surface at any given time is the sum of that coming directly from the sun plus that being scattered by the atmosphere and reflected from the ground or other objects.

Definition

Insolation (W/m^2)

"Insolation" is short for "incident solar radiation" and includes the summation of the energy of all wavelengths incident on a surface. Insolation is given the symbol I, but with subscripts to specify whether it is instantaneous or average, direct beam or diffuse or the total of two, direction of the incident light, and other details associated with the value for insolation. The total amount of power incident on a surface would be the insolation, I (W/m^2 or Btu/hr/ft^2), multiplied by the area of the surface, A (m^2, ft^2).

Solar Constant

The details of the solar spectrum are very important for photovoltaics, selective window glazing for buildings, and photosynthesis. But for applications that absorb all wavelengths and generate heat, only the total incident power (W/m^2, Btu/hr/ft^2), the area under the spectrum curve, is important. The total incident power outside the atmosphere is debated, varies with sunspot activity and varies throughout the year, but the value specified by the ASTM standard is I_{SC} = 1366 W/m^2 (433 Btu/hr/ft^2). Combining this measurement with a sun-earth distance of 1.485×10^{11} m, we could calculate the total amount of energy leaving the sun in all directions as 3.84×10^{26} Watts. The solar constant I_{SC} is measured perpendicular to the direction of the incoming light and is all direct beam radiation.

$$I_{\text{sc}} = \left(1{,}366\frac{W}{m^2}\right)$$

The earth is slightly closer to the sun in winter, resulting in a variation of about 3 percent in the solar constant over the course of a year, from around 1,320 W/m^2 in summer to 1,410 W/m^2 in winter. The equation for insolation measured outside the atmosphere (subscript AMO, for Air Mass Zero) and perpendicular to the direction of the radiation (subscript normal) is

$$I_{\text{AMO, normal}} = (I_{\text{SC}})(1 + 0.033\cos\left(\frac{360n}{365}\right)) \tag{2-17}$$

Or the subsequent and more accurate

$$\begin{aligned} \mathrm{I}_{\text{AMO, normal}} = \left(1366\frac{w}{m^2}\right)&(1.000110 + 0.034221\ \text{cos}t\,B \\ &+ 0.001280\sin B + 0.000719\ \text{cos}t\,2B \\ &+ 0.000077\sin 2B \end{aligned} \tag{2-18}$$

Where in the first equation n is the number of day of year (January 1 = 1; February 1= 32; and so forth up to December 31 = 365) and in the second equation B is the parameter B = (n – 1)360/365 (Chen 2011). These equations quantify the subtle variation of the solar resource outside of the atmosphere as function of day-of-year.

The amount of solar radiation is attenuated from 1,366 W/m^2 outside the atmosphere to around 1,000 W/m^2 (300 Btu/hr/ft^2) by absorption in the atmosphere, and some of the direct beam radiation will be scattered to become diffuse radiation. Consider a solar collector positioned in sunlight as illustrated in Figure 2-8. The collector surface is tilted up from the horizontal at a tilt angle of β (degrees). A normal to the surface is facing off in an azimuth direction that is γ_{surface} degrees west of due south (for east-facing surfaces the value of the surface azimuth angle would be negative). In the Southern Hemisphere this convention would be reversed (east would be positive, west negative).

Direct Normal Insolation, I_{beam} (W/m^2, Btu/hr/ft^2)

Direct beam insolation, also called *direct normal irradiance* (DNI) is the amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the parallel rays that come in a straight line directly from the sun. The amount of irradiance received by a surface is maximized by keeping it normal to incoming radiation. This quantity is of particular interest to concentrating solar collectors, wherein the mirrors or lenses control only the beam radiation. Tracking collector mounts that track the position of the sun across the sky seek to maximize interception of the beam radiation.

The equation for direct beam solar radiation in the plane of the solar collector, $I_{c,\text{beam}}$, is this normal beam radiation multiplied by the cosine of the incident angle

$$I_{c,\text{ beam}} = I_{\text{beam}}\cos\theta \tag{2-19}$$

The "incident angle," θ, is the angle between a normal (perpendicular) to the surface and a line to the sun. The calculation of this angle will be described in a later section below. Direct beam radiation is the part of sunlight responsible for casting shadows, with diffuse sunlight illuminating the interior of the shadow.

Diffuse Solar Insolation, I_{diffuse} (W/m^2, Btu/hr/ft^2)

Some of the radiation beginning above the atmosphere as beam radiation is scattered, or *diffused*, by water droplets and dust

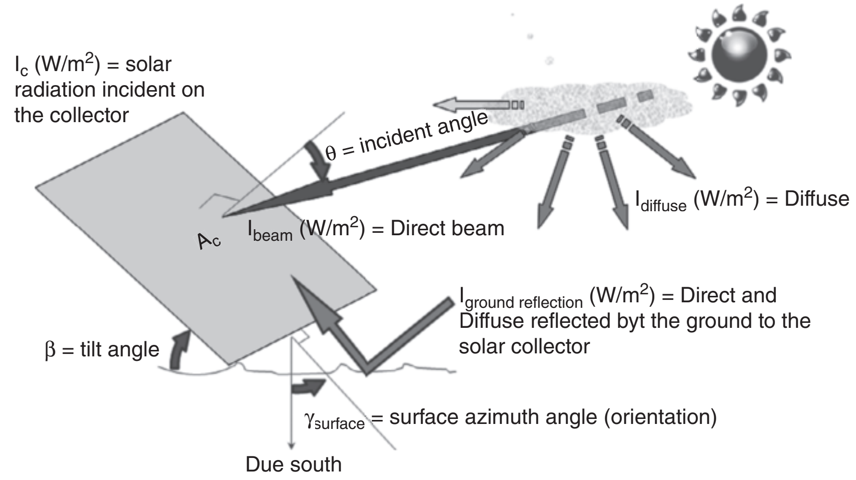


Figure 2-8. Direct beam radiation is scattered by dust and water droplets in the atmosphere, resulting in direct beam, diffuse, and ground-reflected solar radiation incident on the solar collector. (Figure by the author)

as it passes through the atmosphere. This decreases I_{beam} and increases I_{diffuse}. *Diffuse insolation* is the amount of radiation received per unit area by a surface that does not arrive on a direct path from the sun, but is rather *isotropic*, which means it comes equally from all directions.

With this isotropic assumption, the diffuse solar radiation in the plane of the solar collector, $I_{c,\text{diffuse}}$, is the isotropic diffuse radiation multiplied by the radiation view factor of the surface to the sky.

$$I_{c,\text{ diffuse}} = I_{\text{diffuse}}\left(\frac{1+\cos\beta}{2}\right) \qquad \text{(2-20)}$$

There are also anisotropic models in the literature that assume the diffuse is forward scattered if the beam radiation is high, and isotropic if the direct beam radiation is low (Beckman and Duffie 2006).

Ground Reflected Radiation, $I_{\text{ground reflected}}$ (W/m^2, Btu/hr/ft^2)

A third source of solar radiation striking the collector is the beam and diffuse radiation striking the ground in front of the solar collector that is reflected up and to the collector surface. This can be significant for collectors at steep tilt angles and when the ground is covered with snow or otherwise highly reflective.

Ground reflected radiation is given by the following equation

$$I_{c,\text{ ground reflected}} = (I_{\text{beam}}\sin\alpha + I_{\text{diffuse}})\rho_{\text{ground}}\left(\frac{1-\cos\beta}{2}\right) \qquad \text{(2-21)}$$

Global Solar Radiation in the Plane of a Solar Collector Surface

"Global insolation" is the sum of all the radiation striking the collector: direct beam, diffuse and ground reflected. This is the value that is of interest for nonfocusing solar collectors, such as most types of photovoltaic and solar water heating collectors.

$$I_c = I_{c,\text{ beam}} + I_{c,\text{ diffuse}} + I_{c,\text{ ground reflected}} \qquad \text{(2-22)}$$

Regarding focusing collectors, if the sunlight hits a mirror or a lens at a random angle it will be reflected or refracted at a random angle, and so it is only the beam radiation which is harvested by a focusing collector.

INCIDENT ANGLE OF DIRECT BEAM SUN ON A SURFACE

Consider a coordinate system consisting of three unit vectors originating at the solar collector surface. Figure 2-9 illustrates the geometry for calculating incident angle in these coordinates.

> **i_z** is a direction from the center of the earth to our location on the earth, and on in a straight-up direction (the zenith).
>
> **i_y** is perpendicular to **i_z** in the plane of the horizon, and pointing in the south direction.
>
> **i_x** is perdendicular to the other two and pointing east in the plane of the horizon

Within this coordinate system identify the position of two vectors:

> ***N*** is a vector perpendicular ("normal") from the solar collector surface
>
> ***B*** is a vector pointing from the solar collector surface to the sun

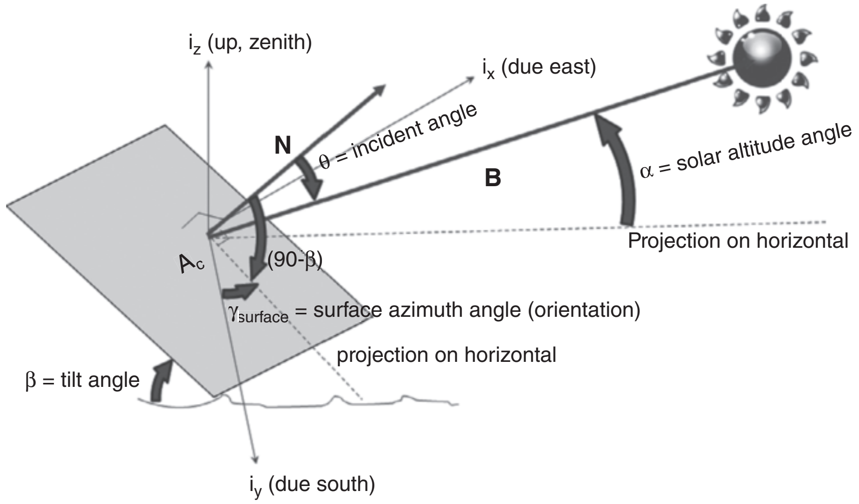


Figure 2-9. The cosine of the incident angle is the dot product of the surface normal, N, and a line to the sun indicated by vector B. (Figure by the author)

Referring to the position of the vectors and the angles illustrated in the figure,

$$\boldsymbol{B} = \cos\alpha \cos\gamma_{\text{solar}}\, \boldsymbol{i_y} + \cos\alpha \cos\gamma_{\text{solar}}\, \boldsymbol{i_x} + \sin\alpha\, \boldsymbol{i_z}$$

and

$$\boldsymbol{N} = \cos(90 - \beta) \cos\gamma_{\text{surface}}\, \boldsymbol{i_y} + \cos(90 - \beta) \sin\gamma_{\text{surface}}\, \boldsymbol{i_x} + \sin(90 - \beta)\boldsymbol{i_z}$$

The dot product between the two vectors ***B*** and ***N*** is evaluated. Say that B and N are both unit vectors of magnitude = 1, so the dot product is just $1 * \cos\theta$:

$$\cos\theta = \boldsymbol{N} \cdot \boldsymbol{B} = \cos\alpha \cos\gamma_{\text{solar}} \cos\gamma_{\text{surface}} \sin\beta + \cos\alpha \sin\gamma_{\text{solar}} \sin\beta \sin\gamma_{\text{surface}} + \sin\alpha \sin\beta_{\text{surface}} \quad (2\text{-}23)$$

Use the trigonometric identity $\cos\gamma_{\text{solar}} \cos\gamma_{\text{surface}} + \sin\gamma_{\text{solar}} \sin\gamma_{\text{surface}} = \cos(\gamma_{\text{solar}} - \gamma_{\text{surface}})$.

$$\cos\theta = \cos\alpha \sin\beta \cos(\gamma_{\text{solar}} - \gamma_{\text{surface}}) + \sin\alpha \sin\beta \quad (2\text{-}24)$$

This gives the cosine of the incident angle as a function of solar altitude and azimuth angle. In terms of the original angles: δ declination (day of year); ω hour angle (time of day); φ latitude; and the angles that describe the position of our surface: β tilt angle; and γ_{surface} surface azimuth orientation, the equation for the incident angle is

$$\cos\theta = \sin\delta \sin\varphi \cos\beta - \sin\delta \cos\varphi \sin\beta \cos\gamma_{\text{surface}} + \cos\delta \cos\varphi \cos\beta \cos\omega - \cos\delta \sin\varphi \sin\beta \cos\gamma_{\text{surface}} \cos\omega + \cos\delta \sin\beta \sin\gamma_{\text{surface}} \sin\omega \quad (2\text{-}25)$$

Equation 2-25 is a general equation for incident angle based on position of the sun and position of the solar collector surface. The angles involved (tilt β and surface azimuth direction γ_{surface}) are defined as illustrated in Figure 2-10. Tracking and positioning alternatives simplify this equation for special circumstances. Several different tracking configurations are illustrated in Figure 2-11. Equations 2-26 through 2-35 below present the incident angle for different tracking alternatives (Taylor and Kreider 1998 and Beckman and Duffie 2006).

Horizontal Surface

For a horizontal surface, the surface normal is pointing straight up, in the zenith direction, so the incident angle in this orientation is also called the zenith angle. The tilt angle is $\beta = 0$ and the surface azimuth, although arbitrary, may also be taken to be $\gamma_{\text{surface}} = 0$. For a horizontal surface the incident angle reduces to

$$\cos\theta = \sin\delta \sin\varphi + \cos\delta \cos\varphi \cos\omega \quad (2\text{-}26)$$

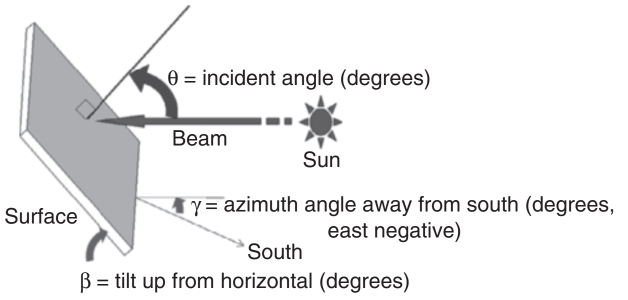


Figure 2-10. Angle of incidence of direct beam insolation on a surface may be calculated given tilt angle, azimuth orientation, latitude, time of day and day of year. (Figure by the author)

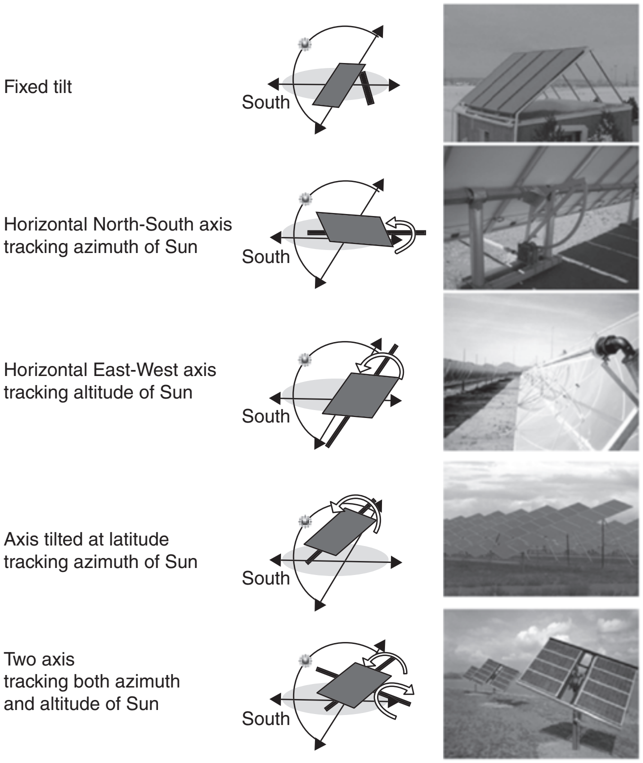


Figure 2-11. Alternative mounting systems for fixed collector position or for tracking the sun across the sky to increase energy production. (Figure by the author)

Vertical Walls

For a vertical wall, the tilt angle $\beta = 90$ degrees. The incident angle as a function of time of day, day of year, and latitude is then

$$\cos\theta = -\sin\delta\cos\varphi\cos\gamma_{\text{surface}} + \cos\delta\sin\varphi\cos\gamma_{\text{surface}}\cos\omega + \cos\delta\sin\gamma_{\text{surface}}\cos\omega \tag{2-27}$$

For walls facing toward the equator, typical of solar heating applications, the tilt angle $\beta = 90$ degrees and also the surface azimuth $\gamma_{\text{surface}} = 0$. The incident angle as a function of time of day, day of year, and latitude is then

$$\cos\theta = -\sin\delta\cos\varphi + \cos\delta\sin\varphi\cos\omega \tag{2-28}$$

Fixed Tilt

The position of surfaces fixed in any orientation is described by the tilt up from the horizontal, β, and the angle between due south and the surface normal. Thus the incident angle is

$$\cos\theta = \cos(\gamma_{\text{solar}} - \gamma_{\text{surface}})\cos\alpha\sin\beta + \sin\alpha\cos\beta \tag{2-29}$$

Note that this requires calculating the solar altitude and azimuth angles first. For a solar collector mounted at a fixed tilt facing toward the equator (south in the northern hemisphere, north in the southern), Duffie and Beckman present a relationship based on the fact that surfaces with slope β have the same angle to the incoming solar beams as a horizontal surface would if located at latitude $\varphi - \beta$ (Beckman and Duffie 2006). In the Northern Hemisphere

$$\cos\theta = \cos(\varphi - \beta)\cos\delta\cos\omega + \sin(\varphi - \beta)\sin\delta \tag{2-30}$$

In the southern hemisphere the sign convention is that latitude is negative, but we want the difference between latitude and tilt so we have to observe the sign in the equation and

$$\cos\theta = \cos(\varphi + \beta)\cos\delta\cos\omega + \sin(\varphi + \beta)\sin\delta \tag{2-31}$$

Which is for use, again, with a negative value of φ south of the equator.

Horizontal East-West Axis Tracking the Altitude of the Sun

In this mounting configuration the axis of rotation is horizontal and running in the east-west direction. As the plane of the array rotates, it tracks the altitude angle of the sun up as it rises in the morning and down as it sets at night.

$$\cos\theta = \sqrt{1 - \cos^2\delta\sin^2\omega} \tag{2-32}$$

Horizontal North-South Axis Tracking the Azimuth of the Sun

In this mounting configuration the axis of rotation is horizontal and running in the north-south direction. The collector faces east in the morning and it rotates to track the azimuth angle of the sun from east to west through the day.

$$\cos\theta = \sqrt{(\sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega)^2 + \cos^2\delta\sin^2\omega} \tag{2-33}$$

Tilted Axis Tracking the Azimuth of the Sun

Called a "polar tracker," the axis is tilted up from the horizontal at a tilt angle equal to the local latitude, $\beta = \varphi$, and the collector rotates to track the azimuth of the sun. The tilted axis of rotation gives the collector good exposure to the altitude of the sun, and the rotation around the axis tracks the azimuth of the sun from east to west through the day. This configuration is almost as good as a two-axis tracker if the tilt angle of the axis is adjusted seasonally.

$$\cos\theta = \cos\delta \tag{2-34}$$

Two-Axis Tracker

In this mounting configuration there is rotation around two axes of rotation. One tracks the altitude angle, and the other tracks the azimuth angle. This keeps the plane of the collector perpendicular to the sun's rays at all times and thus is the maximum resource that could be intercepted over a collector area by tracking.

$$\cos\theta = 1 \tag{2-35}$$

In summary, given measurements or predictions of direct beam and diffuse radiation, and ground reflectance, we can calculate the global (total) solar insolation incident on a surface of any orientation or tracking configuration as a function of time-of-day, day-of-year, and latitude.

Example Calculation of Solar Insolation Incident on a Surface

First, take as our location a latitude of $\varphi = 32$ degrees north and a longitude of 92 degrees west, near Little Rock, Arkansas. Say we have a solar collector tilted up at an angle from the horizontal of $\beta = 32$ degrees and facing toward the equator (south) so that the surface azimuth angle $\gamma_{\text{surface}} = 0$. We wish to compare the output of the fixed tilt collector with that using two-axis tracking, for data corresponding to January 1, near but not precisely the winter solstice. We must first start with measurements of direct beam and diffuse radiation from on-site measurements, satellite measurements, or interpolation of nearby sites. The information listed in Table 2-1 is available as Typical Meteorological Year data for nearby Little Rock, Arkansas, from (NSRDB 1999).

Now from the day-of-year ($n = 1$) and the time-of-day (hour), we can calculate the declination, hour angle, solar altitude, solar azimuth, and incident angle according to Equation 2-29. The results for each angle are listed in Table 2-2.

Now that we know the incident angle for each hour, we can multiply the cosine of that times the direct beam radiation, and add the diffuse and ground reflected insolation to calculate the total global insolation on the solar collector as per Equation 2-22. Note the differences in the magnitude of the beam, diffuse and ground reflected radiation for each hour listed in Table 2-3.

So even on this winter day, when the solar resource could be expected to be a minimum, solar radiation of over 1,000 W/m^2 is incident on this collector around noon. This exemplifies an important lesson about the solar resource: the instantaneous

TABLE 2-1. TMY DATA FOR JANUARY 1, FOR LITTLE ROCK, ARKANSAS

Month	Day	Hour (MST)	Direct beam radiation I_{beam}(W/m^2)	Diffuse horizontal radiation I_{diffuse} (W/m^2)
1	1	1	0	0
1	1	2	0	0
1	1	3	0	0
1	1	4	0	0
1	1	5	0	0
1	1	6	0	0
1	1	7	0	0
1	1	8	199	16
1	1	9	566	47
1	1	10	570	77
1	1	11	590	109
1	1	12	640	123
1	1	13	440	155
1	1	14	727	107
1	1	15	499	99
1	1	16	430	77
1	1	17	49	26
1	1	18	6	2
1	1	19	0	0
1	1	20	0	0
1	1	21	0	0
1	1	22	0	0
1	1	23	0	0
1	1	24	0	0

TABLE 2-2. SOLAR ANGLE CALCULATIONS FOR JANUARY 1, FOR LITTLE ROCK, ARKANSAS

Hour (MST)	Declination Equation 2-6	Hour angle Equation 2-7	Solar altitude angle α (deg) Equation 2-13	Solar azimuth angle γ (deg) Equation 2-16	Incident angle, θ (deg) Equation 2-29
1	–23.01	165.00	–73.97	59.63	135.95
2	–23.01	150.00	–62.02	78.83	132.95
3	–23.01	135.00	–49.38	88.82	128.45
4	–23.01	120.00	–36.69	83.73	116.51
5	–23.01	105.00	–24.15	77.00	102.97
6	–23.01	90.00	–11.96	70.19	89.22
7	–23.01	75.00	–0.29	62.76	75.42
8	–23.01	60.00	10.55	54.18	61.73
9	–23.01	45.00	20.17	43.90	48.39
10	–23.01	30.00	27.96	31.40	35.88
11	–23.01	15.00	33.15	16.53	25.56
12	–23.01	0.00	34.99	0.00	21.01
13	–23.01	–15.00	33.15	–16.53	25.56
14	–23.01	–30.00	27.96	–31.40	35.88
15	–23.01	–45.00	20.17	–43.90	48.39
16	–23.01	–60.00	10.55	–54.18	61.73
17	–23.01	–75.00	–0.29	–62.76	75.42
18	–23.01	–90.00	–11.96	–70.19	89.22
19	–23.01	–105.00	–24.15	–77.00	102.97
20	–23.01	–120.00	–36.69	–83.73	116.51
21	–23.01	–135.00	–49.38	–88.82	128.45
22	–23.01	–150.00	–62.02	–78.83	132.95
23	–23.01	–165.00	–73.97	–59.63	135.95
24	–23.01	–180.00	–81.01	0.00	137.01

TABLE 2-3. CALCULATIONS OF INCIDENT SOLAR RADIATION FOR JANUARY 1, FOR LITTLE ROCK, ARKANSAS

Hour (MST)	$I_{c\ \text{direct}}$ (W/m^2) Equation 2-19	$I_{c\ \text{diffuse}}$ (W/m^2) Equation 2-20	Global horizontal (W/m^2)	$I_{c\ \text{ground reflect}}$ (W/m^2) Equation 2-21	I_c (W/m^2) Equation 2-22
1	0.00	0.00	0.00	0.00	0.00
2	0.00	0.00	0.00	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.00	0.00	0.00
8	94.24	14.63	52.44	0.90	109.77
9	375.87	42.98	242.15	4.14	422.99
10	461.85	70.42	344.24	5.89	538.16
11	532.28	99.68	431.62	7.38	639.34
12	597.44	112.49	489.98	8.38	718.31

(continued)

TABLE 2-3. ***(Continued)***

Hour (MST)	$I_{c\ \text{direct}}$ (W/m^2) Equation 2-19	$I_{c\ \text{diffuse}}$ (W/m^2) Equation 2-20	Global horizontal (W/m^2)	$I_{c\ \text{ground reflect}}$ (W/m^2) Equation 2-21	I_c (W/m^2) Equation 2-22
13	396.95	141.75	395.60	6.76	545.47
14	589.07	97.85	447.84	7.66	694.58
15	331.38	90.54	271.05	4.63	426.55
16	203.64	70.42	155.74	2.66	276.72
17	12.33	23.78	25.75	0.44	36.55
18	0.08	1.83	0.76	0.01	1.92
19	0.00	0.00	0.00	0.00	0.00
20	0.00	0.00	0.00	0.00	0.00
21	0.00	0.00	0.00	0.00	0.00
22	0.00	0.00	0.00	0.00	0.00
23	0.00	0.00	0.00	0.00	0.00
24	0.00	0.00	0.00	0.00	0.00

TABLE 2-4. CALCULATION OF INCIDENT SOLAR RADIATION ON A TWO-AXIS TRACKING COLLECTOR, FOR JANUARY 1, FOR LITTLE ROCK, ARKANSAS

Hour (MST)	Incident angle, θ (deg) Equation 2-35	Tilt angle, β	$I_{c\ \text{direct}}$ (W/m^2) Equation 2-19	$I_{c\ \text{diffuse}}$ (W/m^2) Equation 2-20	Global horizontal (W/m^2)	$I_{c\ \text{ground reflect}}$ (W/m^2) Equation 2-21	I_c (W/m^2) Equation 2-22
1	0.00	163	0.00	0.00	0.00	0.00	0.00
2	0.00	155	0.00	0.00	0.00	0.00	0.00
3	0.00	139	0.00	0.00	0.00	0.00	0.00
4	0.00	126	0.00	0.00	0.00	0.00	0.00
5	0.00	114	0.00	0.00	0.00	0.00	0.00
6	0.00	101	0.00	0.00	0.00	0.00	0.00
7	0.00	90	0.00	0.00	0.00	0.00	0.00
8	0.00	79	199.00	9.47	52.44	4.28	212.75
9	0.00	69	566.00	31.60	242.15	15.87	613.47
10	0.00	62	570.00	56.55	344.24	18.28	644.83
11	0.00	56	590.00	84.30	431.62	19.56	693.86
12	0.00	55	640.00	96.76	489.98	20.90	757.67
13	0.00	56	440.00	119.88	395.60	17.93	577.81
14	0.00	62	727.00	78.58	447.84	23.79	829.37
15	0.00	69	499.00	66.57	271.05	17.76	583.33
16	0.00	79	430.00	45.55	155.74	12.72	488.27
17	0.00	90	49.00	12.93	25.75	2.59	64.52
18	0.00	101	6.00	0.79	0.76	0.09	6.88
19	0.00	114	0.00	0.00	0.00	0.00	0.00
20	0.00	126	0.00	0.00	0.00	0.00	0.00
21	0.00	139	0.00	0.00	0.00	0.00	0.00
22	0.00	152	0.00	0.00	0.00	0.00	0.00
23	0.00	163	0.00	0.00	0.00	0.00	0.00
24	0.00	171	0.00	0.00	0.00	0.00	0.00

intensity, or power output of a solar collector, can occur at any time of year. If the incident angle θ is zero, the intensity of sunlight is constant at around 1,000 W/m^2, and what varies most is the hours over which it occurs.

Finally, we wish to compare to a case which involves two-axis tracking to keep the collector area "normal" to the sun's rays, thus keeping the incident angle equal to zero $\theta = 0$, and maximizing the amount of sunlight the surface area of the collector could intercept. Incident angle is as per Equation 2-35. Now for each hour we have a different tilt angle β for use in the diffuse and ground reflected equations. This hourly tilt angle is calculated from the solar altitude angle as $\beta = (90 - \alpha)$. Results for the case with 2-axis tracking are listed in Table 2-4.

Finally, to compare the solar energy incident on the fixed orientation to that of the two-axis tracker, we produce a chart displaying the two values of I_c for the day as illustrated in Figure 2-12.

In this example the fixed tilt and two-axis tracking have about the same incident solar at noon, but in the case of the fixed tilt, the incident solar is attenuated by the cosine of the incident angle, while the two-axis tracker maximizes the solar incident on the tracking collector. For this example day, January 1, the fixed tilt intercepted 4.41 kWh/m^2, while the two-axis tracker intercepted 5.47 kWh/m^2, considerably more. Another way to view this figure is that the fixed tilt produces around 1,000 W/m^2 for about 4.41 hours in the day, and the tracking produces around 1,000 W/m^2 for around 5.47 hours. This is an approximation obviously, but a useful one as we will see later in the chapters of this book related to each technology.

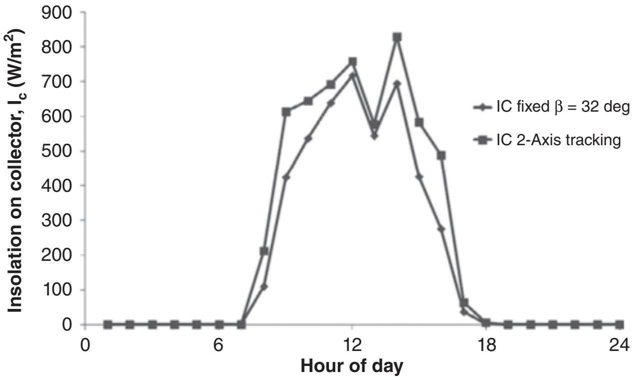


Figure 2-12. Comparison of solar insolation incident on a collector with fixed tilt $\beta = 32$, south facing, and two-axis tracking. At noon they are nearly the same, but the tracking provides full solar exposure from sunrise to sunset. (Figure by the author)

The effect of which tracking option you select depends on many factors. Each has advantages and disadvantages depending on whether the intent is to maximize energy delivery over the course of the year, or to match a heating profile that provides more heat in winter but less in summer. To complete this example, the graph of Figure 2-13 shows how the daily value calculated for one single day (as exemplified here for January 1) would vary for the 12 months of the year, using data for Little Rock, Arkansas from (Marion and Wilcox 1994).

It is seen from figure 2-13 that that vertical glass facing toward the equator (south in the northern hemisphere) would be good for space heating because it is maximum in the winter months and less in summer. Much more energy can be collected with tracking configuration, especially in summer when the sun cuts a high arc from east to west. In winter the sun is lower in the sky, and any surface at a steep tilt facing toward the equator intercepts most of the available radiation.

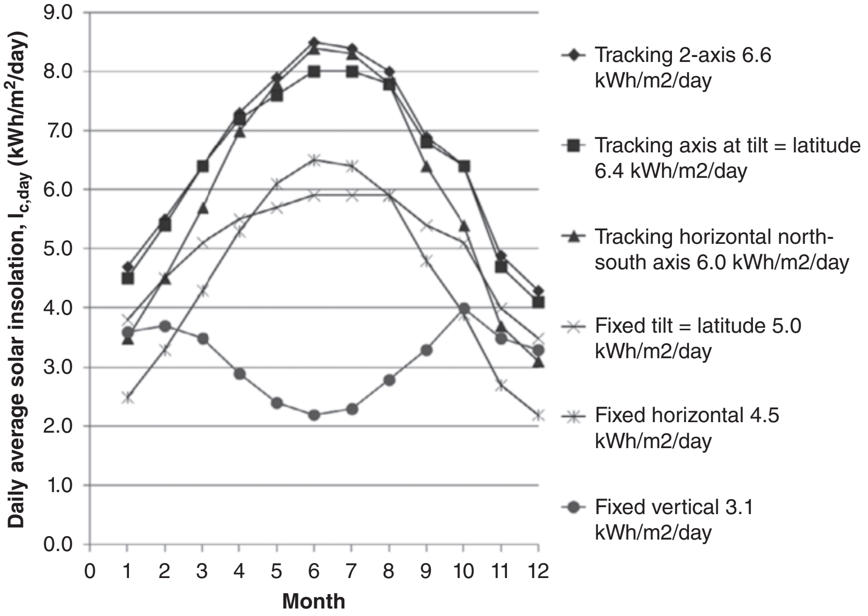


Figure 2-13. Comparison of average daily solar insolation, $I_{c,day}$ (kWh/m^2/day) for different fixed-tilt and tracking alternatives. Example data is for Little Rock, Arkansas. Annual averages are listed in the legend. Figure by the author using data from (Marion and Wilcox 1994)

THE EFFECT OF SHADE

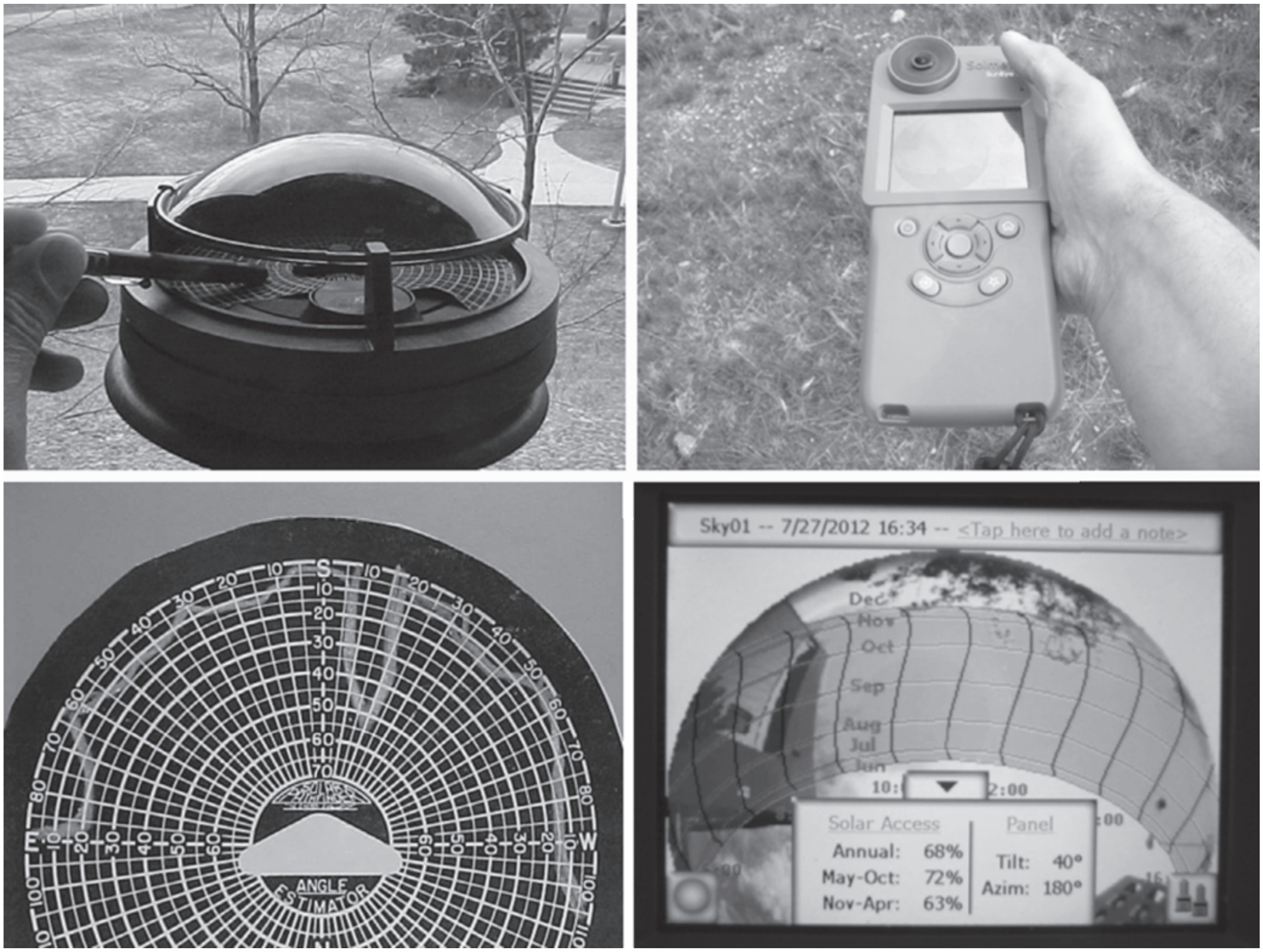
Shading is very detrimental to the performance of any type of solar collection device. Shading essentially eliminates the solar gain and should be avoided. It is generally not practical to avoid all shading at all times, however. Some shading may be unavoidably imposed by a mountain, a building, or a utility pole. In these cases there is a relatively easy way to calculate the effect of shading on annual energy delivery.

Most shading objects do not move, although a tree may have leaves in autumn but not in spring. Even if a tree loses its leaves, it still blocks a lot of the sun. It is convenient to simply record the surrounding shading objects as a modification to the height of the horizon. A chart must be made that records the top of the horizon, the top of all the shading objects, as an altitude angle associated with each azimuth angle. This chart of horizon altitude as a function of azimuth direction could be entered into a computer program or used with manual chart methods to estimate the effect of the shading on annual energy delivery.

Figure 2-14 shows two types of instruments to measure the effects of shading objects. The Solar Pathfinder is a clear spherical dome which reflects the horizon, and under which a user can sketch out the horizon of shading objects on a paper chart. The Solmetric Suneye is an electronic device with a fish-eye lens and image processing to estimate the percentage reduction in insolation due to shading. Both instruments display the horizon on a chart that shows the position of the sun in the sky at each hour, and for each month. Such a chart is specific to each latitude.

In our simple treatment, the effect of shading is this: if, for a given solar azimuth angle, the altitude angle of the shading object is higher than the solar altitude angle α, then the direct beam component is zero ($I_{\text{beam}} = 0$) and the insolation incident on the collector is only the diffuse component. In other words, if the sun is below the horizon of shading objects, the direct beam is zero and only the diffuse is used to estimate the solar power.

Shading is a phenomenon which occurs at a point, and it is difficult to calculate the effect of a shading object over the entire area of the solar collector. You make take several measurements



Sky01 -- 7/27/2012 16:34 -- <Tap here to add a note>

Solar Access
Annual: 68%
May-Oct: 72%
Nov-Apr: 63%

Panel
Tilt: 40°
Azim: 180°

Figure 2-14. Examples of optical and digital instruments to record shading objects on the horizon at a location. On the left is the Solar Pathfinder and a capture of the shading horizon on the National Mall in Washington DC; and on the right is the Solmetric SunEye with calculation of 68 percent access (32 percent loss) due to shade of a nearby building. (Photos by the author) over the area and average them, and report shading at the worse-case location. Sophisticated calculation techniques to evaluate the effect of shading and reflections from multiple surrounding buildings on areas (of a building or of a solar array) are described by Pritpal Singh (2005).

A useful angle related to calculating shading is the *profile angle*. If you only cared about shading at noon, you wouldn't need the profile angle, but at other hours it is a projection of a shading object onto a plane through the due-south (or due-north in the Southern Hemisphere). Figure 2-15 illustrates the profile angle on an overhang device, which provides desirable shade, and between rows of solar collectors, when shade would be undesirable. By projecting the shading on the due-south plane we are able to figure out the amount of the window or solar collector shaded by an object.

The equation for profile angle is (Taylor and Kreider 1998)

$$\tan P = \frac{\tan\alpha}{\cos\gamma_{\text{solar}}} \tag{2-36}$$

Example Calculation: Spacing Rows of Collectors to Avoid Shading

An example of the calculation of the profile angle arises in determining the spacing in between rows of solar collectors required to avoid shading. Avoiding any shading whatsoever is not practical, so let's say that we seek to avoid shading between the hours of 10 a.m. and 2 p.m. on the shortest day of the year, when the sun is lowest in the sky. Most of the available insolation on a fixed tilt would occur during these hours.

Say that the length of each of the solar collector arrays, L_c, is 6 m (19.7 ft), and that the location is at a latitude of $\varphi = 40$ north. At 10 a.m.t he hour angle would be 30 degrees. The declination we know already is –23.45 on the shortest day of the year. The collector tilt angle is $\beta = 40$ degrees. The profile angle and required collector spacing are calculated as shown in Table 2-5.

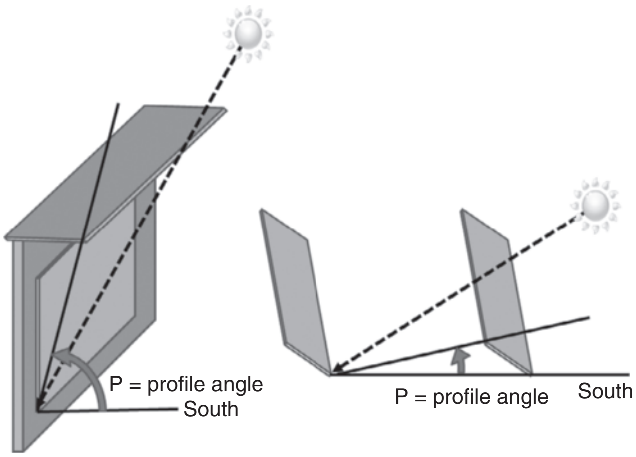


Figure 2-15. The "profile angle" is the projection of the edge of a shading object onto the due-south plane, which makes it easy to calculate the amount of a window or solar collector shaded by an object. (Figure by the author)

TABLE 2-5. EXAMPLE CALCULATION OF SPACING BETWEEN ROWS OF COLLECTORS TO AVOID SHADING

Latitude, ϕ	40 degrees north
Date	23-Dec winter solstice
Julian day	357 days
Declination Equation 2-6	–23.5 degrees
Solar altitude angle Equation 2-13 $\alpha = a \sin(\cos - 23.45 \cos 40 \cos 30 + \sin - 23.45 \sin 40) =$	20.7 degrees
Solar azimuth angle Equation 2-16 $\gamma_{\text{solar}} = a \sin(\cos - 23.45 \sin 30/\cos 20.7)$	29.4 degrees
Profile angle Equation 2-36 $P = \tan^{-1}(\tan\alpha/\cos\gamma_{\text{surface}})$	23.4 degrees
Spacing $S = L_c(\sin(\beta + P)/\sin P) =$ $(6\text{m}) \sin(40 + 23.4)/\sin(23.4)$	13.5 m (44.3 ft)

SOLAR RESOURCE MEASUREMENT

The earliest instrument to measure solar radiation was a glass sphere that focused light and burned a line across a sheet of paper as the sun moved across the sky. Such a record would show only whether the sun is out or not, which is actually pretty useful, considering how direct beam insolation occurs: either it is perpendicular and at its full value or the sun is behind a cloud and you are not getting enough insolation to power your solar energy device. Global (beam + diffuse) radiation on a surface is attenuated, however, by the cosine of the incident angle and light clouds and haze in the atmosphere, such that the value of incident solar insolation could be any value between 0 and 1,000 W/m^2, with values greater than 1,000 also measured occasionally.

Instruments used in solar resource assessment are illustrated in Figure 2-16. The instrument used to measure global radiation is the pyranometer. Modern instruments use calibrated temperature sensors (such as Eppley PSP) or semiconductors (such as Licor 200), to measure the intensity of the solar radiation and generate an electronic signal that can be automatically recorded. These instruments must be carefully calibrated and the calibration maintained at annual intervals. Inexpensive handheld versions are impossible to maintain accurate calibration on, in my experience.

The instrument used to measure direct beam radiation is called a "pyrheliometer." It consists of a solar energy sensor at the base of a collimating tube. The tube allows straight beams to pass through it to the sensor, but the blackened walls of the

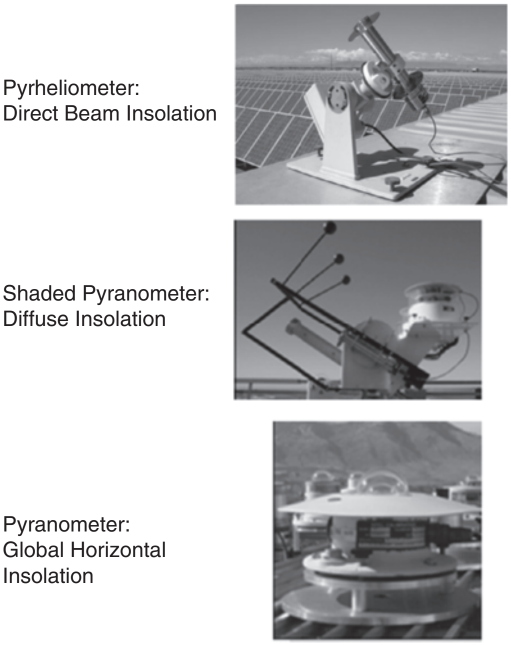


Figure 2-16. Instruments used to measure solar radiation include pyrheliometer to measure direct beam, shaded pyranometer to measure diffuse, and pyranometer to measure global insolation. (Photo by Tom Stoffel, courtesy of DOE/NREL, Pix# 06821, 06231, 06232)

tube absorb any diffuse light. The instrument must be installed on a tracking mount to keep the tube facing toward the sun.

The instrument used to measure diffuse radiation is called a "shadow-band pyranometer" or a "shadow-disk pyranometer." These use a disc or a moving band to shade the solar sensor from the direct beam radiation, but it is exposed to diffuse radiation coming from all other parts of the sky.

Satellites are also used to analyze solar radiation reflected back from earth from clouds and to derive an estimate of the incident solar resource on the ground. Figure 2-17 illustrates, conceptually, the major aspects of solar resource mapping by satellite. The models used to analyze the satellite data are simple at each layer (for example, a linear function of the signal), but are very complex in the way the many layers of analysis are required to derive an estimate of incident solar. These models are validated by comparison to an extensive array of measurement stations on the ground. Although the satellite models should be viewed as approximate, they yield a very high-resolution depiction of how the solar resource is distributed over a large area. Two satellite programs provide data: Meteosat in Europe and GOES in the US, and data is available through the associated space agencies DLR and NASA (www.goes.noaa.gov). Richard Perez at the State University of New York, Albany, has been a leader in developing these models and making the information available to decision makers that need the information (Perez 2012).

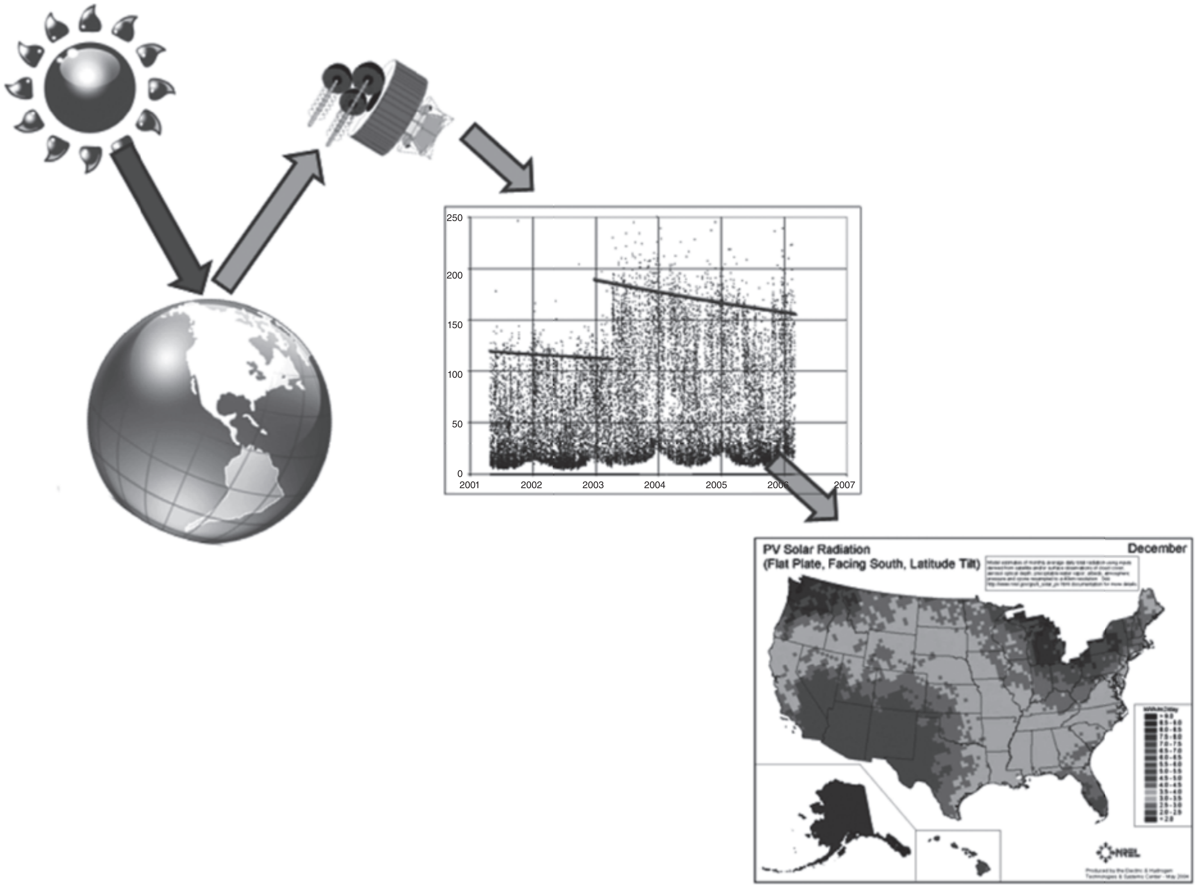


Figure 2-17. Solar energy reflected by clouds is recorded by satellite sensors and used to inform complex models of incident solar radiation.

SOLAR RESOURCE MAPS AND DATA

The standard solar spectrum with a solar constant of 1,366 W/m^2 combined with the solar geometry and the incident angle could be used to generate a theoretical estimate of solar availability on any surface at any location. However, the effect of clouds is very pronounced and any such estimate would be very approximate and optimistic. Thus we refer to empirical sources of climate data that include the direct beam and diffuse solar radiation values needed for the calculation of insolation incident on a solar collector. Data comes from measurements that have been made at or near a monitoring site, processed satellite data, or sophisticated interpolations between data sources. The number of sites for which data is available and the quality of the data available has improved dramatically with research and information technology (Walker et al. 2003).

United Nations Environment Programme (UNEP) Solar and Wind Energy Resource Assessment (SWERA) project involves participants from 13 countries (maps.nrel.gov/SWERA). SWERA provides renewable energy resource information online. SWERA publishes maps of monthly and annual direct normal irradiance (DNI) and other solar parameters at a 40-km resolution for Africa, South and Central America, China, India, and Southeast Asia. In addition, hourly modeled data from surface stations, and typical meteorological years (TMYs), are available for some countries.

The NASA Solar Data Analysis Center (umbra.nascom.nasa.gov/) provides data for concentrating solar power technologies.

The NASA Surface Meteorology and Solar Energy (SSE) site (eosweb.larc.nasa.gov/sse/) provides solar resource data for nonfocusing and also concentrating solar power applications based on satellite cloud modeling, which is done on a 100-km spatial resolution. Data are available for any location in the world and include several climate data parameters. Figure 2-18 illustrates monthly world maps of the solar resource from this NASA website.

SOLEMI—Solar Energy Mining (www.solemi.de/home.html) provides high-quality irradiance data. This service from the German Aerospace Center (DLR) is mainly based on Meteosat-data with a nominal spatial resolution of 2.5 km and half-hourly temporal resolution.

Solar radiation maps and an hourly time series data are available for almost half of the earth's surface, but there are many sources of data maintained by government agencies, universities, research organizations. Research into database and local sources of information is a regular part of a project feasibility study.

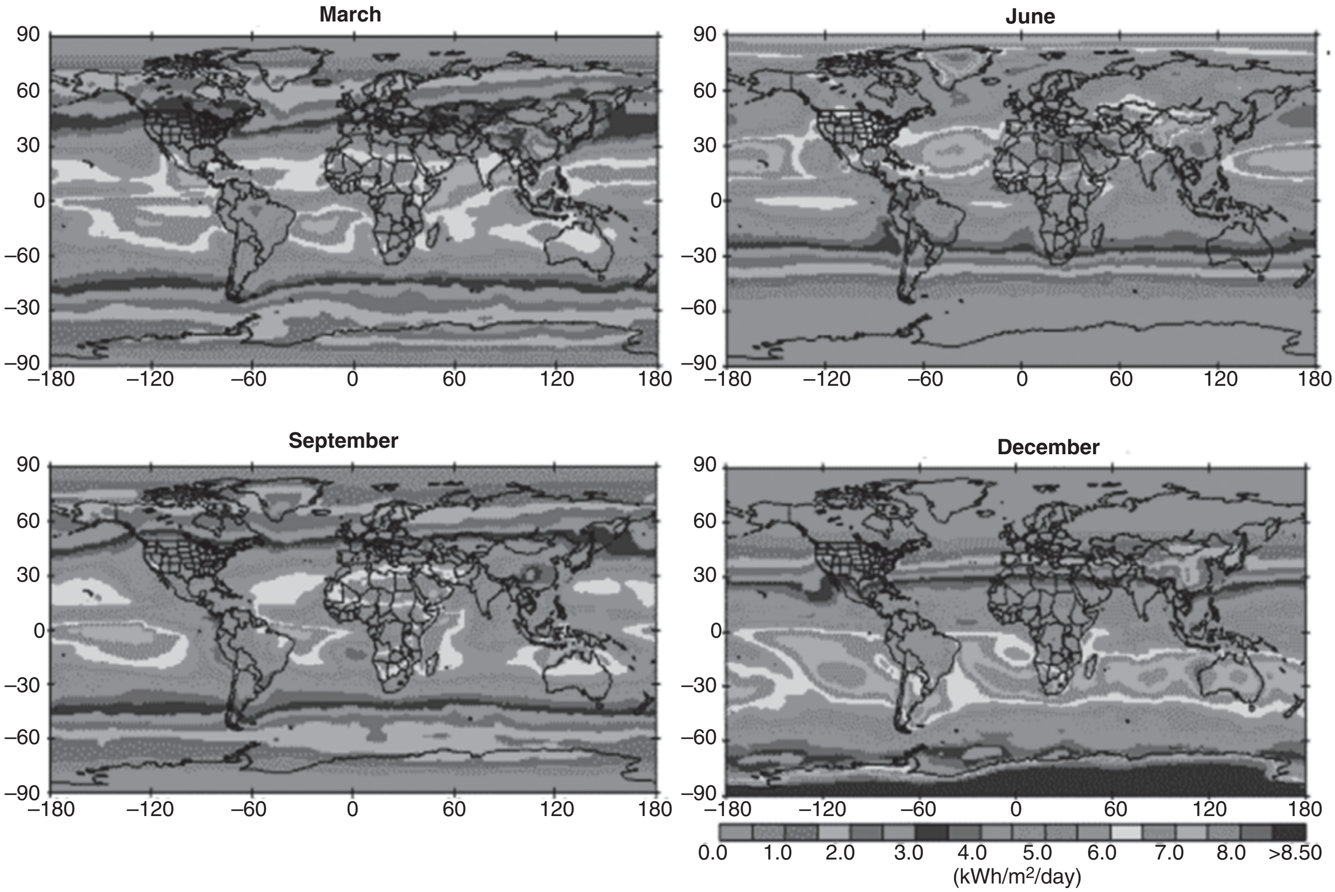


Figure 2-18. Examples of monthly solar resource maps by the NASA Surface Meteorological and Solar Energy site. (Figure by the author from eosweb.larc.nasa.gov/sse/)

NREL's Renewable Resource Data Center (rredc.nrel.gov) makes time series and map data available and also includes many links to other resource data and map sources. Even though it is old, I find the NREL solar radiation data manual very useful (rredc.nrel.gov/solar/pubs/redbook/). Solar resource GIS map data and GIs map software tools are available at www.nrel.gov/GIS.

TYPICAL METEOROLOGICAL YEAR (TMY) WEATHER DATA

TMY is a data format and methodology that includes many measures of climate data, including direct beam and diffuse solar radiation, that are useful for solar energy calculations. Hourly data sets of meteorological and solar radiation data for a "typical" one-year period are derived from long-term time series (>20 years) by selecting time periods with the same average magnitude as the long-term average. This approach maintains the random nature and peak extremes of the underlying data but collapses all the years of collected data down into one annual set of 8,760 hourly values (24 hours per day * 365 days/year).

Definition of P50

Analyzing multiple years of data gives rise to the idea of a "P" value associated with the annual information. A P50 means that 50 percent of the years of data have resource value greater than the reported value for the resource (kWh/m^2/year of solar energy gain). A P90 means that 90 percent of the years have a solar resource value greater than the reported value. Engineers refer to the P50 value. Bankers refer to the P90 value.

TMY data fields contain information about the location (WMO ID#, city and country name, time zone, latitude and longitude, elevation); solar radiation (Top of Atmosphere, DNI, GHI, diffuse, illuminance, sky cover); and other meteorological data (temperature, dew point, relative humidity, pressure, wind direction and speed, visibility, ceiling height, present weather, precipitable water, aerosol optical depth, snow depth, days since last snow). The three sequential versions TMY1, TMY2, and TMY3 are not interchangeable due to changes to the time standard and data fields, but may be converted one to another with utilities. The TMY3 data sets and users' manual with complete detail were produced by NREL's Electric Systems Center under the Solar Resource Characterization Project, which is funded and monitored by the U.S. Department of Energy's Energy Efficiency and Renewable Energy Office. Data is available for 1021 sites in the US and many international locations as well. Data may be identified by site number or name and downloaded from rredc.nrel.gov/solar/old_data/nsrdb/1991–2005/tmy3/ (RREDC 2005).

FORECASTING THE SOLAR RESOURCE HOURS OR DAYS INTO THE FUTURE

Operators of utility transmission and distribution systems arrange for power delivery in advance of the instantaneous requirement for it. Such arrangements specify a high certainty that the power will be delivered at the required time. Forecasting helps solar energy sell into that market. Without advance notice of the power delivery from a solar power plant, a large amount of spinning reserve is required on the utility system. Reliable forecasting offers to reduce the amount of spinning reserve (reserve yes, spinning no). Methods have been developed to predict the output of a solar plant in a given location based on conventional weather forecasts; observing the trajectory of clouds in the sky; and modeling the fluid mechanics and psychometrics (condensation) of the atmosphere.

Conventional Weather Forecasting

The output of a solar plant may be correlated with data from conventional weather forecasting services. Services developed to forecast precipitation have evolved into products that forecast solar and wind energy as well. Sophisticated models have several input parameters and forecast global horizontal insolation, direct normal insolation, and diffuse horizontal insolation (W/m^2). A Web-based service called Weather Analytics (weatheranalytics.com/renewableforecast.html) provides a forecast of these parameters for each of 172 hours into the future.

Sky Imaging

Instruments have been developed to take a digital image of the sky dome (wide-angle lens), and use image processing to identify clouds moving across the sky. A vector motion (speed and direction) is calculated for the shading effect of the cloud on the sensor, and software is used to predict shading of the solar plant several hours in the future. This gives time for the operator of the utility system to start and dispatch a gas turbine generator, or to increase the output of a coal-fired power plant. Figure 2-19 shows an instrument used to record the sky image and the resulting cloud pattern. Yankee Environmental Systems in Turner Falls, Massachusetts makes an instrument that uses a spherical mirror to capture an image of the total sky. Such instruments work with software that uses three-dimensional models to predict cloud trajectory.

Numerical Weather Prediction

Numerical weather prediction is based on simulating the condition of the atmosphere with models based on the

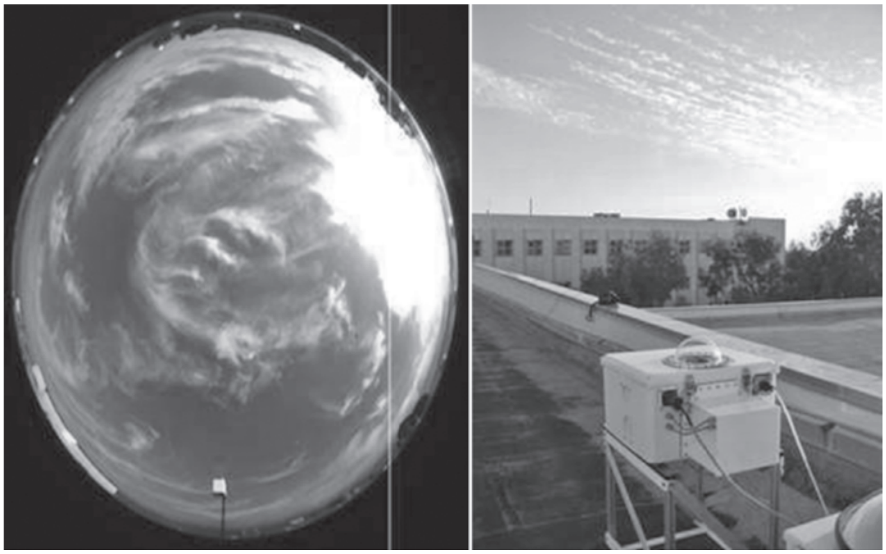


Figure 2-19. Total sky imaging instrument used to identify and track the approach of clouds. (Image provided by Patrick J. Mathiesen, Bryan Urquhart, and Jan Kleissl, courtesy of University of California, San Diego)

physical laws of motion and thermodynamics. Parameters involved include temperature profile in the atmosphere, and surface temperature. The models simulate heating and mixing in the atmosphere which are primarily responsible for the formation of clouds. The weather and forecasting model (WRF) represents the state of the art in such numerical weather prediction. Figure 2-20 is an image predicting cloud cover resulting from cloud modeling in the San Diego area of Southern California (Mathiesen and Kleissl 2012).

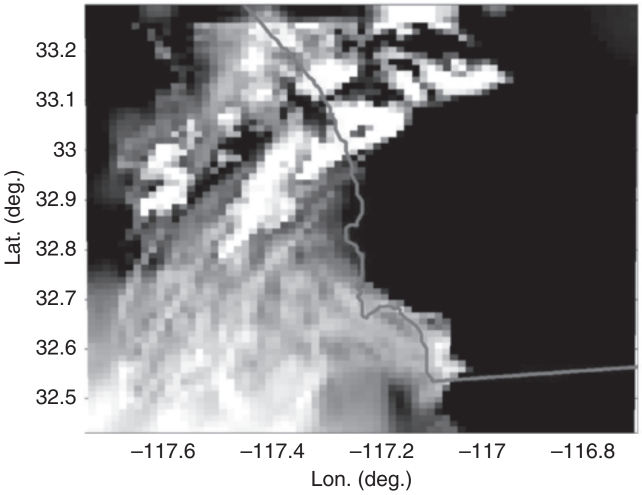


Figure 2-20. The numerical weather prediction model WRF can predict cloud formation at a high resolution of 1.3 km. (Image provided by Patrick J. Mathiesen, Bryan Urquhart, and Jan Kleissl, Courtesy of University of California, San Diego)

DIAGNOSIS OF SOLAR ENERGY SYSTEM PERFORMANCE USING SOLAR RESOURCE DATA

A quick comparison of the energy delivered by a solar system over a given period of time to the incident solar resource averaged over the same time period may be used to evaluate whether a system is performing as expected or not. The PV Power Map is a monthly average solar resource map generated by Solar Anywhere Services (cleanpower.com) using SolarGIS models (geomodelsolar.au) that combine satellite-measured solar data with PV system simulation capabilities. The map is published in *Solar Today* magazine (ases.org; solartoday.org) every month. If you can remember to write down the energy delivery of your system the month before (kWh/month), you can compare it to the prediction of the map to ascertain if your system performed as it should have over that month. For example, in the July/August 2012 issue of *Solar Today,* the map is for April 2012, and I see that a PV system should have produced 130 kWh per kW of capacity for the month in my location. So my 2.7 kW system should have provided 351 kWh. In reality, it delivered 333 kWh, which is 6 percent less than the map data. The comparison gives me confidence the system is working as it should, considering that the map is based on specific system assumptions including the tilt angle of the solar collector.

COMPUTER TOOLS FOR ANALYSIS OF SOLAR POSITION AND SOLAR RESOURCES

Table 2-6 presents a comparison of some computer tools related to solar resource assessment from the on-line tools directory apps1.eere.energy.gov/buildings/tools_directory/

TABLE 2-6. COMPARISON OF SOFTWARE TOOLS TO EVALUATE SOLAR RESOURCES

	Non-proprietary	Visible or well-described calculations	Extensive weather data	Well-tested	Free or Low cost	User support	Recently updated	Documentation
Climate 1			*	*		*	*	*
Geospatial Toolkit	*			*	*	*	*	*
Meteonorm			*	*		*	*	*
SolarGIS database version 1.8			*	*		*	*	*
SunAngle Professional Suite		*		*		*	*	*

(DOE OBT 2011) plus experience of the author. This comparison is certainly not inclusive of all programs available and is not intended to indicate that one is any better than another; rather that each has appropriate applications. The programs are compared according to the following criteria:

- Nonproprietary: computer program is available to competing commercial interests.
- Calculations may be checked: calculations which are used to generate the results should be visible in a spreadsheet form or well-described in program documentation.
- Climate data: extensive weather data for multiple countries or access to climate data is facilitated.
- Well tested: computer program used on many projects to vet bugs and ensure usefulness and confidence in the results.
- Cost: free or low cost.
- User support: contact information is valid and support and training are available.
- Recently updated: program is reflective of current models and computer systems.
- Documentation: complete reference material is available.

A short description is provided for each tool along with other information, including expertise required, users, audience, input, output, computer platforms, programming language, strengths, weaknesses, technical contact, and availability.

Climate 1

Climate 1 is a climate database and software to access and visualize solar data. The database contains more than 1,200 station data sets distributed all over the globe.

- Expertise required: No special training required
- Audience: Solar building energy analysis; geography; teaching
- Input: Location data and data from satellite databases and models.
- Output: Temperature, relative humidity, precipitation, global radiation, sun hours, wind speed and direction. Data is displayed graphically on the screen and the data can be exported for other applications.
- Computer platform: MS Windows PC.
- Strengths: Collects data from several databases to get global coverage.
- Contact: eclim; Address: Augustastrasse 24 Koln D-51065 Germany. Telephone: +49 (221) 372445; E-mail: dellef.hennings@eclim.de. Website: www.climate1.com.
- Cost: varies from $30 for personal to $150 for professional.

Geospatial Toolkit (NREL GsT)

The Geospatial Toolkit (GsT) is a map-based software tool developed at NREL that provides data and tools to perform solar energy resource assessments. The tool is an interface to make GIS-based data available to users without GIS expertise. The tool includes solar resource maps but also allows the user to overlay layers such as roads, transmission lines, and ground slopes to prospect for project location opportunities. Land-use planners can run queries to see how much land in an area meets specified criteria. Clicking on a point accesses point data such as solar resource values for a site that may be exported to solar analysis applications such as HOMER (see chapter 3). The toolkit is available for 16 countries currently, including China and India.

- Expertise required: Familiarity with Internet applications and data file handling—no special training or GIS capability required.
- Audience: Analysts who need data for a specific location; planners who want to find out candidate land areas.
- Input: Map-based navigation.
- Output: Monthly average solar data and hourly data files for export including direct beam and global horizontal insolation.

- Computer platform: Internet application; any Web browser should work.
- Strengths: Quick and easy resource, well-documented.
- Contact: Website: www.nrel.gov/international/geospatial_toolkits.html.
- Cost: Free download from website.

Meteonorm

Meteonorm is a database of some 1,200 sites worldwide, with sophisticated interpolation between the sites.

- Expertise required: No special training required
- Audience: Engineers, architects, teachers, planners.
- Input: Select from a specific location or enter longitude and latitude for interpolation.
- Output: A table pops up as the data is processed, and then exported to several choices of format (TMY, etc.) or custom format. Data includes global horizontal and diffuse radiation as well as temperature and wind data.
- Computer platform: Windows 2000, XP, and Vista.
- Strengths: Provides a file in desired format for any location by interpolation.
- Contact: Meteotest, E-mail: office@meteotest.ch; Website: www.meteonorm.com.
- Cost: $520.

SolarGIS Database version 1.8

GeoModel Solar operates a high-resolution meteorological database of satellite-derived solar radiation and meteorological data called "SolarGIS." The database includes the following parameters: global horizontal irradiance and direct normal irradiance; air temperature, relative humidity, wind speed and direction. Coverage of solar radiation data is limited to Europe, Africa, Asia, West Australia, and Latin America, but the company expects to offer data for the whole planet soon.

- Expertise required: Service delivers data, maps and other products, consumer literacy with software not required.
- Audience: Solar energy project planners; performance monitoring, mapping and planning.
- Input: Location data and data from satellite databases and models.
- Output: Global horizontal and direct beam solar radiation time-series data in ASCII CSV, SAM, PVSYST, and other data formats. Spatial data could be delivered in ESRI ASCII GRID format, GeoTIFF, Google Earth KML/KMZ, or NetCDF data formats.
- Computer platform: Data delivery service.
- Strengths: Well-structured and documented.
- Contact: GeoModel Solar, Pionierska 15, 831 02 Bratislava, Slovakia; Telephone: +421 2 492 12 491; fax: +421 2 492 12 423; E-mail: contact@geomodel.eu; Website: geomodelsolar.eu/home.
- Cost: Varies with data product, some free maps.

SunAngle Professional Suite

Provides time correction and calculation of all the solar angles (declination, hour angle, solar altitude, solar azimuth). Professional Suite version of SunAngle includes well-documented HTML/JavaScript and Microsoft Excel versions of SunAngle, plus a detailed technical manual explaining how to perform all of the underlying calculations.

- Expertise required: Knowledge of HTML, JavaScript, and/or Microsoft Excel.
- Audience: Users who need a quick calculation of the solar position or to customize the software in other applications.
- Input: Longitude, latitude, time of day, date.
- Output: Hour angle, declination, solar altitude angle, solar azimuth angle, day length, times of sunrise/sunset, and angle of incidence on a surface.
- Computer platform: HTML/JavaScript web browser; Microsoft Excel depending on version.
- Strengths: Quick and easy resource, well-documented.
- Contact: Sustainable By Design, Telephone: 1 (206) 925–9290; E-mail: christopher@susdesign.com; Website: www.susdesign.com/sunangle/ Cost: $40; download from website.

STANDARDS RELATED TO SOLAR RESOURCE ASSESSMENT

Standards related to solar resource assessment are described in (RREDC 2012).

In 2000, the American Society for Testing and Materials developed an "Air-Mass Zero (AM 0)" reference spectrum (ASTM E-490) for use by the aerospace community. That standard solar spectral irradiance is based on data from satellites, space shuttle missions, high-altitude aircraft, rocket soundings, ground-based solar telescopes, and modeled spectral irradiance. The integrated spectral irradiance has been made to conform to the value of the solar constant accepted by the space community; which is 1,366.1 W/m^2. Other ASTM standards relate to air mass other than zero (1.0 and 1.5). Each of the standards is available for purchase at (www.astm.org/).

- ASTM E490-00a (2006) Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables
- ASTM G173-03 (2008) Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface and also the associated detailed tables of emissive power at each wavelength
- ASTM G173-03 Tables: Extraterrestrial Spectrum, Terrestrial Global 37° South-facing Tilt and Direct Normal + Circumsolar
- ASTM Standard G159-98 Standard Tables for References Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37° Tilted Surface

NREL also published a set of guidelines related to collection and use of solar resource data: *Concentrating Solar Power: Best Practices Handbook for the Collection and Use of Solar Resource Data* (www.nrel.gov/docs/fy10osti/47465.pdf).

REFERENCES

ASTM. 2006. “Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables.” West Conshohocken, PA: American Society of Testing and Materials. www.astm.org/Standards/E490.htm.

——— 2008. “Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface.” West Conshohocken, PA: American Society of Testing and Materials.www.astm.org/Standards/G173.htm.

Beckman, W., and J. Duffie. 2006. *Solar Engineering of Thermal Processes.* 3rd ed. New York: John Wiley and Sons.

Butti, K., and John Perlin, 1980. *Golden Thread: 2500 Years of Solar Architecture and Technology.* Palo Alto, CA: Cheshire Books.

Chen, C. J. 2011. *Physics of Solar Energy.* Hoboken, NJ: John Wiley and Sons

Davidson, T., and C. Turkington. 2012. “Sunburn.” *Encyclopedia of Children’s Health.* www.healthofchildren.com/S/Sunburn.html (accessed July 27, 2012).

Decher, R. 1997. *Dirperct Energy Conversion: Fundamentals of Electric Power Production.* New York: Oxford University Press.

DOE OBT. 2011. “Tools Directory.” Office of Building Technologies. http://apps1.eere.energy.gov/buildings/tools_directory/ (accessed March 16, 2012).

LLNL. 2007. “From Core to Corona: the Layers of the Sun.” Lawrence Livermore National Laboratory. Fus Ed Web Fusion Energy Education. fusedweb.llnl.gov/cpep/chart_pages/5.plasmas/sunlayers.html (accessed July 2, 2012)

Marion, W., and S. Wilcox. 1994. *Solar Radiation Data Manual for Flat Plate and Concentrating Collectors.* Edited by M. A. Dunlap. Golden, CO: NREL.

Mathiesen, P., and J. Kleissl. 2012. “Development and Validation of an Operational, Cloud-Assimilating Numerical Weather Prediction Model for Solar Irradiance Forecasting.” ASME 6th Conference on Energy Sustainability, San Diego, CA.

NASA LARC. 2012. “Surface Meteorology and Solar Energy.” NASA.gov http://eosweb.larc.nasa.gov/sse/ (accessed March 4, 2012).

NobelPrize.org. 2012. “Nobel Prize in Physics 1967.” www.nobelprize.org/nobel_prizes/physics/laureates/1967/bethe-bio.html (accessed July 3, 2012).

NSRDB. 1999. “TMY2 Weather Data.” National Solar Radiation Database. rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/ (accessed July 15, 2012).

Perez, R. 2012. “Papers in Solar Resource Assessment.” Richard Perez faculty web page: www.asrc.cestm.albany.edu/perez (accessed July 16, 2012).

Renne, D., R. George, S. Wilcox, T. Stoffel, D. Myers, and D. Heimiller. 2008. *Solar Resource Assessment.* Golden, CO: National Renewable Energy Laboratory.

RREDC. 2005. “TMY3 Data and User Manual.” National Solar Radiation Data Base. rredc.nrel.gov/solar/old_data/nsrdb/1991–2005/tmy3/ (accessed July 15, 2012).

——— 2012. “Other AM0 Spectra.” Solar Spectra: Air Mass Zero. rredc.nrel.gov/solar/spectra/am0/references.html

Singh, P. 2005. “Accurate Building Integrated Photovoltaic System (BIPV) Architectural Design Tool.” www59.homepage.villanova.edu/shveta.kantamsetti/P3-Project.htm (accessed July 15, 2012).

Taylor, M., and J. Kreider. 1998. *Principles of Solar Energy Applications.* 3rd ed. Printed by the University of Colorado Bookstore, Boulder Colorado.

Walker, A., D. Renee,, S. Bilo, C. Kutscher, D. Barley, J. Burch, et al. 2003. “Advances in Solar Buildings.” *Journal of Solar Energy Engineering* (125): 236–44.

Wikipedia. 2012. “Law of Cosines.” en.wikipedia.org/wiki/Law_of_cosines (accessed July 14, 2012).

3

Photovoltaics (PV, Solar Electricity)

Teaching in rural Nepal, I had only a small kerosene lamp, called a bati, which I used late into the night grading papers, after which I would notice a ring of soot around each nostril left by the smoke. Finally, I got a PV battery charger that would recharge four AA-size batteries in a day, and I used the batteries to power a lamp and also a radio. That small PV system, simple and inexpensive as it was, made a big difference in my health and productivity. According to the International Energy Agency (IEA 2011), 1.6 billion people, 20 percent of the world's population, live without the utility and convenience of electricity. According to the same set of statistics, 1.2 billion of these people live in sunny areas of Asia and Africa. Photovoltaics are a space-age technology, but they may be deployed in even the most undeveloped areas. Many parts of the world are at a decision point as to which energy infrastructure to invest in. Grid power and a utility bill may not be the right solution for a subsistence farmer, if, with the right tools, he can harvest his own solar power. He might first want a light, then a radio, then perhaps a television or refrigerator. His daughter would need a computer and fast Internet access. These small conveniences remain inaccessible because our poor farmer cannot afford the cost to install a utility power line to his farm. Solar PV allows him to purchase only the small amount of energy he can afford.

Photo is Greek for light and *voltaics* refers to electricity, so the term "photovoltaics" refers to the conversion of light energy directly into electricity. PV devices are fabricated into "modules," each producing a voltage and direct current. PV Modules are mounted in arrays and wired together. Generation of electric power is coincident with incident light, and the power is used on-site by feeding the power into a building electrical panel. Power in excess of that required by the building load is delivered back onto the utility system in a grid-connected application or stored in batteries in an off-grid application. Other components include an inverter to convert the direct current to alternating current compatible with most building systems and appliances, and electrical hardware such as conductors, conduit, fuses or breakers, disconnects, and meters.

For applications that do not require a lot of power, PV/battery systems are often sufficient to provide reliable power. For large loads, the cost of installing enough solar modules and batteries to serve the load over extended cloudy periods is excessive, and a "hybrid" system, where a generator fueled by diesel fuel or propane provides reliability and the solar modules provide most of the energy, is recommended. In grid-connected applications (distributed generation), rooftop PV systems usually meet a small fraction of the total building power requirements, although many buildings have been built with enough PV to totally offset their power consumption: so called "net-zero buildings." As PV becomes more common, cases are emerging where the utility circuit cannot accept all the power from a large number of PV systems, and how to integrate a significant amount of intermittent renewable energy resources into the utility system is a very active area of research.

Different types of PV cells have been invented, each with its own cost and performance advantages. Investing in PV companies has been risky business for me, because a company with a promising technology is shortly eclipsed by a company with a newer, even more promising technology. The main difference between types of PV is the material that they are made of and the processes used to manufacture them. Standards are so specific that products are all much the same in terms of physical strength and electrical integrity—cost, efficiency, and longevity are the main differentiators.

Photovoltaics may be deployed on almost any type of building or electrical load. Photovoltaics are most cost-effective in small applications where the cost of primary batteries or extending the utility grid system to the site is cost-prohibitive. The market for PV may be described as a diffusion from niche applications to bulk energy:

- Space satellites, which are exposed to plenty of sun and for which other sources of power are impossible.
- Small electrical devices, such as watches and calculators, where the cost and inconvenience of replacing primary batteries is high. For example, if an AA battery costs $0.45 and delivers 1.5 Wh of energy, that is an astonishing $300/kWh for the cost of energy. Now that I have a solar powered watch, my days of driving from mall to mall looking for a replacement battery are over. Given the convenience of it, I am surprised that all battery powered toys and gadgets don't have a solar-powered version.
- Electrical devices which must operate independent of utility power and use power for controls, communications, or data acquisition—loads that have a high value but are not very energy-intensive. For example, irrigation controls that only open and close a valve but don't pump water. Another example is the solar-powered emergency call boxes which are ubiquitous on public roadways.
- Loads which can use the solar power when it is available and avoid the need for batteries. One of the earliest examples is watering livestock from a well, where the water is stored in a tank for use.
- Remote houses and facilities where the cost of installing a power line from the utility far exceeds the cost of a PV system, but for which reliable power at conventional voltage is required. These are often installed with a fueled generator, too, to reduce the required investment in solar.
- Utility-connected distributed generation applications, both residential and commercial, where the value of the PV is high due to high conventional energy costs and where public incentives bear a large part of the cost.
- Utility-scale bulk power, where solar competes with other sources of bulk power (coal, natural gas, nuclear) based on their cost and environmental attributes.

As the cost of PV comes down, larger systems in competition with more conventional power sources may become cost-effective, but are currently supported by compelling incentive payments offered by utilities as required by government regulators. Investment of the ratepayers' money in incentives for solar is paying off. The price of solar has dropped dramatically due to the scale of the market and the competition fostered by incentive programs. And PV is now seen as a recognized resource in utility system integrated resource planning.

The earliest conversion of sunlight to electricity was by thermo-electric effect (a thermocouple of dissimilar metals) and later by heat engines early in the 1800s. Solar cells made of selenium were fabricated in the late 1880s, and subsequently found use in light meters for photography. But the efficiency was very low and concepts of quantum mechanics had to emerge before people understood how they worked and how to improve on them. In 1954, Darryl Chapin, who was trying to improve selenium cells, was introduced to Calvin Fuller, who was making rectifiers from silicon by adding impurities, by Gordon Pearson, who had observed the effect of light on the silicon cells. They were able to produce a cell of 6 percent efficiency, which was enough to generate a useful amount of power (Butti and Perlin 1980). The three researchers were awarded a patent and are recognized as the inventors of PV. None of the three had all the information individually—they had to work as a team to make their invention.

The first solar cells manufactured cost $1,500/Watt. At that rate, the only cost-effective application, although an important one, was satellites in outer space, where sunlight was persistent and plentiful and other sources of power unavailable. A company called Hoffman Electronics fabricated arrays for spacecraft in the late 1950s and early 1960s. Several terrestrial applications were demonstrated in the 1970s, focused on remote loads such as a lighthouse in Japan and village power in Africa. As a college intern in 1982, I helped Dave Waddington of the Solar Energy Research Institute build a water pumping station with 2 kW of PV and a wind turbine in a project funded by the United Nations. By the early 1980s the industry had grown to several MW/year of production, and Atlantic Richfield Co. (ARCO) demonstrated a 1 MW utility-scale PV system in California. It's interesting to me that several of these early PV companies were oil companies like ARCO Solar, Mobil Solar, and Solar Power Corporation by Exxon. I guess they fancied themselves energy companies rather than just oil companies, or maybe they were so flush with windfall profits at that time that they were investing in everything.

The US began federal research into PV at the Jet Propulsion Laboratory in California in the early 1970s, and opened the Solar Energy Research Institute (now the National Renewable Energy Laboratory) in Colorado in 1979. PV has long been the largest research program at NREL. The National Center for Photovoltaics (NCPV) was created in 1996 to coordinate the expertise of NREL, Sandia National Laboratories, Brookhaven National Laboratory, Georgia Institute of Technology, the University of Delaware, Southeast Regional Experiment Station, Southwest Technology Development Institute, and other university and industry partners. Today, the NCPV is working toward the goal of making large-scale solar energy systems cost-competitive with other energy sources by 2020. NCPV continues to research the underlying physics of the devices, works with industry on developing new processing techniques, and administers deployment and demonstration projects (NREL 2012).

In the 1990s, Japan administered a residential PV incentive program that grew the market there, and in 2000 Germany instituted a feed-in-tariff with generous terms for the purchase of PV electricity. Spain was also a leader in the growth of the PV market in Europe. Some states in the US, such as California and New Jersey, had already implemented compelling incentive

Definition

Definition of "kW" and "MW" of PV

The size of PV projects are often described in kiloWatts (kW) and annual manufacturing production capacity and market for PV are often described in terms of megawatts (MW), or even gigawatts (GW). Each solar module has a nameplate, which lists out how much power the module generates under standard test conditions (STC). STC specifies conditions of full sun and cool temperature, which tends to overstate PV output, and generally the output of a module will be less than this nameplate rating. The sum of the nameplate capacities of all the PV panels manufactured by all the factories (supply), or installed in all the projects (market demand), is reported in the literature in units of "MW" of supply or demand. It is as if all the panels being considered were to be laid out in the sun under standard conditions, they would generate the reported number of MW of power. So, rather than square meters or square feet of area, PV is bought and sold, and system sizes are described, in units of power in kW or MW; the power the solar hardware is capable of generating under standard test conditions.

programs, but the market for PV in the US really increased after favorable tax credits and tax depreciation were implemented by the Energy Policy Act of 2005. The 30 percent US Federal Investment Tax Credit available since 2005 was extended for residential and commercial solar water heating systems through 2016, evidence of continuing public policy in support of solar in the US.

For a time, the US was the largest producer of PV until Japanese annual production exceeded the US at 80 MW in 1999. In 2002, European annual production of 135 MW also surpassed US production (Maycock, 2006). Starting in 2006, China and Taiwan began to ramp up manufacturing capacity. By 2010, worldwide production capacity of PV had grown to an astonishing 17,400 MW per year. In 2010 China and Taiwan accounted for 53 percent of PV supply, and Europe accounted for 80 percent of demand. Although eclipsed by the tremendous growth in other countries, an impressive 1,000 MW (6 percent of world supply) was produced in the US and 1,400 MW (8 percent of world demand) was installed in the US in 2012 (EERE DOE 2012). The US market almost doubled in size to 1,855 MW in 2011 and is expected to continue growing.

From 1982 to 2004, most of the PV projects that I worked on were off-grid projects. The grid-connected projects were demonstration projects, many only a few kW in size. Early in my career I never expected to see large grid-connected systems of even 1 MW size—but the regulations and incentives introduced in the US in 2005 were compelling, and in 2011 there were 28 individual PV projects in the US greater than 10 MW each (EERE DOE 2012). As illustrated in figure 3-1, the off-grid market (where utility power is not available) now represents only 3 percent of the market. Now 97 percent of the market is grid-connected, and utility-scale systems meet or exceed commercial and residential installations in terms of installed capacity (MW; US Energy Information Administration 2011b).

Grid-connected systems are certainly less expensive and easier to implement than off-grid systems. The grid connection means that the PV does not need to be big enough to carry the full load, and any excess energy generated by the PV may feed back into the grid for a credit. This eliminates the need for batteries and simplifies the components needed to complete a system. It also eliminates the need for a fossil-fueled generator on-site with its maintenance requirements and environmental impacts. Many utilities offer *net metering*, where excess energy delivered to the grid may be used back at night or at a later date at the same retail value. Others credit the energy they receive from a PV system at their *avoided cost*, which is the savings to the utility of not having to generate that power. Still others offer no credit for excess PV power and may even prohibit the introduction of such power to their system. The type of utility (public owned,

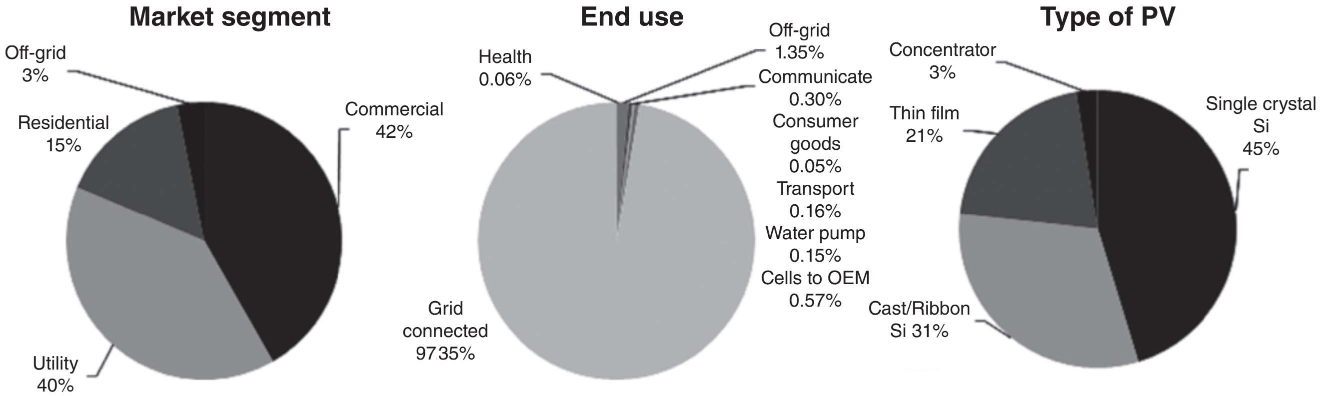


Figure 3-1. Statistics reported by EIA show that large utility-scale installations have become a large part of the US market for photovoltaics. Breakdown is by MW of installed capacity, total capacity = 1,282 MW, data for 2009. (Figure by the author using data from US Energy Information Administration 2011b and utility market segment updated from DOE EERE 2012; OEM refers to PV used in other equipment)

municipal, rural electric cooperative) determines the regulations under which they operate. Net-metering policies are an incentive for PV that is paid for by the other ratepayers of a utility, and limits to this generosity have already been reached in Hawaii and other areas that have already implemented a lot of solar energy. There are also physical limits of how much PV power a given utility circuit can accept from a multitude of PV systems on a sunny day. So, in the long term, as PV becomes more common on buildings, for both technical and economic reasons, not everyone can net meter. Strategies such as energy storage (batteries), already discussed in Chapter 1, would be required to reach a very high penetration of PV within the utility system. In 2010, 4,000 MW of cumulative installed PV capacity provided a measly 0.10 percent of US electric demand, but the goal of the Department of Energy's Sunshot Initiative is to increase PV's contribution to 11 percent of US demand (302,000 MW of cumulative installed capacity) by the year 2030. Most analysts believe that it is possible to provide 10 to 15 percent of total power from PV into the utility grid without major changes to the utility system configuration and operations.

PHOTOVOLTAIC CELLS AND MODULES

Many types of PV devices have been fabricated using different materials, and the means by which a PV cell generates electricity can be described in generic terms without specifying the materials. But the general explanation is abstract, and I think it is easier to understand a particular example using silicon, phosphorous and boron as the materials involved. This was the first type of cell built in 1954, and it is still quite significant in the market.

Band Gap of a Semiconductor Material

Silicon is a semiconductor, which means sometimes it conducts electricity and sometimes it does not. It conducts electricity when energy sufficient to raise an electron from the valence band to the conduction band is provided by a photon of light. The required amount of energy is called the "band gap" and given the symbol $\varepsilon_{\text{gap.}}$ In insulating materials, such as rubber, the band gap is so large that the material would burn if we added enough energy to raise an electron to the conduction band. In conductors, such as metals, the valence band and conduction band overlap so that it takes no additional energy to free a conducting electron. For semiconductors such as silicon, the gap between the valence band and conduction band is "just right," big enough to separate positive and negative charges for us but small enough to be provided by photons of sunlight without damaging the material.

In the solar resource section of this book we described how light is described both as a wave and a particle (photon), with short-wavelength light having more energetic photons than long-wavelength light. So light near the blue part of the spectrum frees an electron, whereas even a brighter light of red color passes right through without freeing an electron. If a photon of energy greater than the band gap is absorbed as an electron is raised from the valence band to the conduction band, then the photon energy in excess of the band gap is dissipated as heat and the electron retains only the energy level of the band gap. For example, if a photon of 2 eV is absorbed in Silicon with a band gap of 1.1 eV, the remaining 0.9 eV is manifest as heat and not useful in the creation of electric power. Germanium, another natural semiconductor, has a band gap of 0.67 eV, so less energetic photons (more toward the red part of the spectrum) can free an electron in germanium. Strategies to improve the efficiency of a PV device include:

- Use materials with higher band gaps to make more effective use of the higher energy photons in the blue and ultraviolet parts of the solar spectrum
- Use materials with lower band gaps to use photons of the red and infrared parts of the solar spectrum.
- Combine different materials with different band gaps to both harvest more photons and make more effective use of each harvested photon.

Figure 3-2 is a conceptual diagram of the energy of a photon raising an electron from the valence band to the conduction band, leaving the atom with a positive charge as the electron takes one negative charge away. The positive charge is called a "hole," because it is characterized as the absence of an electron. Holes also move in the material, but by passing an electron from a neighboring stationary atom. Thus, electrons have a much higher mobility than holes, but movement of both electrons and holes contributes to the electrical current of a PV cell.

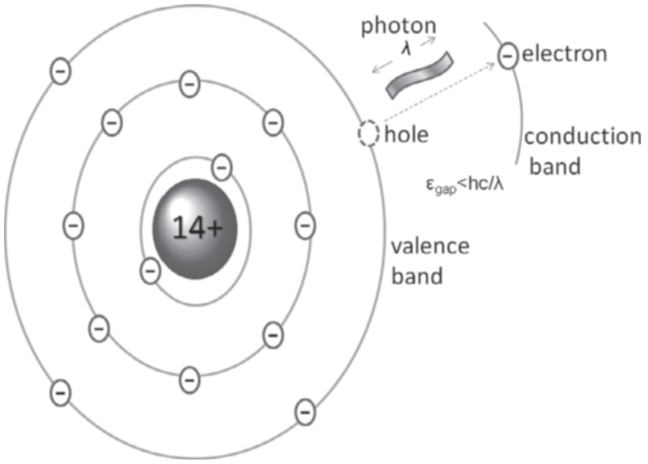


Figure 3-2. An atom of silicon has four valence electrons. A light photon of sufficient energy can raise one of these electrons from the valence band to the conduction band, where it is free to conduct electricity in the material. (Figure by the author)

Crystalline Structure

In amorphous silicon (no crystal structure), there are too many un-bonded electrons and the energy of any photon absorbed is lost as heat. As we will see, it is possible to create a PV device using amorphous silicon, but only with measures to control this and at a substantial penalty to efficiency. So a crystalline structure is important to the operating principal of many types of PV cells. Silicon has an atomic number of 14, which means 14 protons in the nucleus of the atom and 14 surrounding electrons. Each proton has a positive charge and each electron has a negative charge.

The first energy level is occupied by two electrons; the next level by eight; and the third layer can accommodate eight, too, but there are only four left to fill this outer level. These four are called "valence" electrons. They form bonds, thus called "covalent" bonds, with four surrounding silicon atoms to complete the third energy level with eight valence electrons around each silicon atom. This gives the silicon a crystalline structure with a repeating pattern of arranged atoms. It is the "periodicity" of the crystal, the repeating pattern, which extends the energy level discussion of an individual atom to that of the whole crystal.

The P-N Junction

Figure 3-3 shows each silicon atom sharing four valence electrons with its four neighboring atoms. In pure silicon, if a photon of sufficient energy raised an electron from the valence band to the conduction band it would just fall back into a hole and dissipate its energy as heat. In order to separate the electrons from the holes and establish an electric current, the silicon is "doped" by introducing other elements, in this example boron and phosphorous. Boron is mixed with the molten silicon prior to the crystal-growing step. The concentration of boron in silicon is on the order of 2×10^{16} boron atoms per cm^3, much less than 1 percent of the silicon mass. Boron only has three valence electrons. So where a boron atom appears in the silicon crystal there is a gap where an electron should be. This gap is not a "hole," since the atom still has a neutral charge (number of negative electrons still equals number of positive protons). Since it is characterized by the lack of an electron, this silicon doped with boron is called an "acceptor" (because it can accept an additional electron) or "p-type" semiconductor. Once the singe crystal is cut into a wafer, it is baked in an oven with phosphorous and the phosphorous soaks into one side of the wafer. At a depth of 1 micrometer into the surface the concentration of phosphorous atoms would be on the order of 10^{18} atoms of phosphorous/cm^3, which is much more than the boron, thus overcoming the effect of the boron in that top layer, but still less than 1 percent of the silicon mass. Phosphorous has five valence electrons, only four of which complete the bonds of the crystalline structure, so there is an extra electron which is not engaged in a covalent bond. This layer is called a *donor* or *n-type* semiconductor. The interface where these two types come together is called the *p-n junction* (Decher 1997).

Diffusion is the physical process by which items move from areas of high concentration to areas of low concentration. An example is putting a drop of ink into a still glass of water—you can watch the ink diffuse in the liquid without stirring. Diffusion also occurs in solids, albeit at a much lesser rate. So the extra electrons on the side doped with phosphorous will diffuse into the side doped with boron. There are few free electrons on the boron side of the p-n junction to be pulled back to the

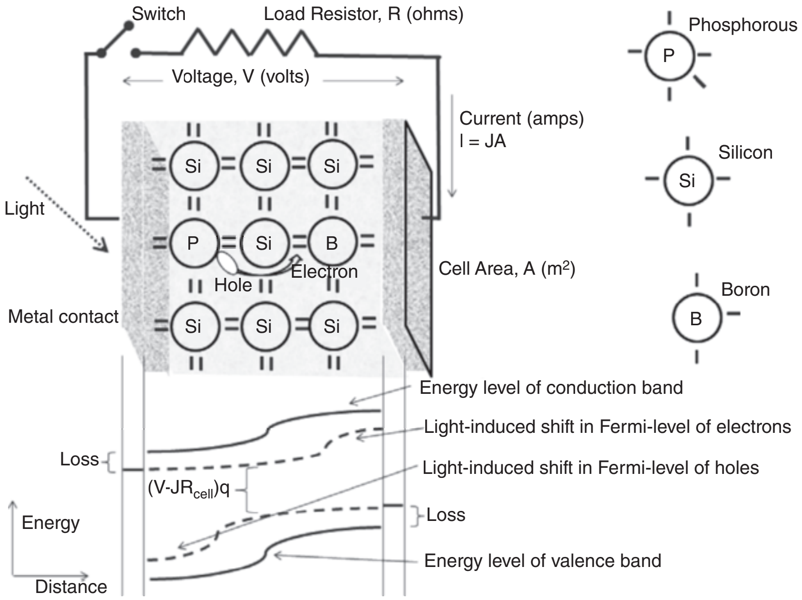


Figure 3-3. The positive-negative junction (p-n junction) is created by doping silicon, which has four valence electrons with boron, which has three, and phosphorous, which has five. The difference causes an electric field at the junction (p-n junction) between the two and a voltage at the metal contacts. (Figure by the author)

phosphorous side, and electrons that have crossed the p-n junction repel additional electrons from following them due to the accumulation of negative charge on the boron side and the resulting electrostatic force. Due to the extra electrons (compared to the number of positive charges in the nuclei of the atoms), the side of the junction doped with boron takes on a negative charge, and due to the departure of electrons, the side doped with phosphorous takes on a positive charge, creating the voltage source for the solar energy device. The p-n junction so formed thus prevents electrons from moving from the phosphorous side directly to the boron side, and similarly prevents holes from moving from the boron side directly to the phosphorous side. Thus the p-n junction makes a one-way gate and in some literature is called a *barrier* rather than a junction. But electrons can get to the other side by going through an external circuit, and in the process can convert their elevated energy level to do some useful work for us.

The study of energy levels is a study in probability statistics. We don't know the exact energy level that a particular electron will be in, but we can calculate the probability of an electron being in a particular energy level based on the assumption that all possible states are equally probable. Enrico Fermi figured out the distribution of energy levels as a function of temperature. The probability of a system being in energy interval $\Delta\varepsilon$ is $e^{\Delta\varepsilon/kT}$, where *T* is temperature in absolute units (K, R) and k is Boltzmann's constant, a physical constant that relates energy level to temperature (8.617×10^{-5} eV/K). The *Fermi energy level* is defined as the energy level which has a 50 percent chance of an electron being at that energy level—some will have more energy, some will have less. The Fermi level has a value equal to another energy level used in chemistry called the *chemical potential*. So, in a sense, light phenomenon is converted to chemical phenomenon, and then to electrical phenomenon (Decher 1997).

Metal Contacts on PV Cell

The Fermi levels at the boundaries of the semiconductor material are not the same as the Fermi levels of electrons in the electrical contacts, which are made of metal and at the same temperature, so there is an unavoidable loss of voltage going from the positive metal contact to the phosphorous side and another loss going from the boron side to the negative metal contact. It is this voltage manifest at the metal contacts to the cell that is useful to us. Metal contacts applied to the front (phosphorous) side of the PV cell must be very thin wires so that they do not block the incoming sunlight, while the back contact may be solid metal. The positive voltage appears at the front contact and the negative voltage at the back contact. Front contacts may also be made from a layer of material which is transparent to light but still conducts electricity. Such material is rare because free electrons in a conductor offer lots of energy states to absorb photons, but tin oxide doped with fluorine is an example of a transparent conducting oxide used in PV panels. In the manufacture of thin film devices that involve deposition of the photovoltaic material directly onto glass, use of a transparent conducting material for the front electrical contact is essential (Luque and Hegedus 2011).

VOLTAGE AND CURRENT CHARACTERISTICS OF PV DEVICES (THE i-v CURVE)

Photovoltaics are unique among electric generators in that both the voltage and current (amps) change with environmental conditions and with the resistance of the load. An understanding of the dependencies and the interaction of current and voltage is essential to the proper layout and operation of a PV system.

OPEN-CIRCUIT VOLTAGE AND OPERATING VOLTAGE OF A PV CELL

Voltage depends more than anything else on the band-gap energy of the material, that is, how much energy we have to put in to separate an electron (–) from a hole (+). Band-gap energy has units of *electron volts* (eV), which describes its definition: the energy to raise one electron by 1 volt potential. Looking at the units, you would think you could divide the band-gap energy by the charge of one electron to calculate the voltage. And as a first approximation this is correct, although actual voltage is reduced by temperature effects which we will discuss. While the band gap of silicon is 1.1 eV, voltage from a silicon PV cell is on the order of 0.6 volts. More precisely, the difference in energy between the electrons at the Fermi level in on the boron side and the holes at the Fermi level of the phosphorous side is the source of the cell voltage.

This difference in Fermi energy levels divided by the charge of an electron gives the voltage at the boundary of the cell. As light shines on the cell, the Fermi level of electrons on the boron side is raised closer to that of the conduction band and the Fermi level of holes on the phosphorous side is lowered, creating the voltage.

William Shockley won the Nobel Prize in 1956 for his discovery of energy band-gap properties in single crystal semiconductors, which led to the revolution in electronics and computers and to solar cells, too (Shockley and Queisser 1961; Nobel Prize Foundation 2012). If James Watt's steam engine epitomized energy in the industrial age, PV cells epitomize energy in the electronics age. Shockley discovered the relationships governing electric voltage and current, which have been further developed by subsequent researchers, but still form the basis of much of the characterization and performance improvements in PV cells.

The reader is referred to the literature for a complete description of the physics (Fraas and Partain 2010; Luque and Hegedus 2011), but in order to reveal some important characteristics we consider a few of most important equations here. The open circuit voltage, v_{oc}, with the switch in the above figure in the *open* position, is

$$v_{oc} = \frac{\varepsilon_{gap}}{q} + \left(\frac{2kT}{q}\right)\ln\left[\frac{\Delta n_{light}}{(N_C N_V)^{1/2}}\right] \tag{3-1}$$

Where Δn_{light} is the increase in the concentration of electrons induced by light ($1/cm^3$), and N_C and N_V are the densities of conduction band states and valence band states, respectively (also in units of $1/\text{cm}^3$). Equation 3-1 offers an opportunity to explain two important characteristics of PV:

- As temperature increases, voltage goes down linearly.
  The argument of the ln function is always less than 1, so the value of the second term is always negative and subtracts from the band-gap voltage. In practice, we do not use this equation to calculate voltage as a function of temperature, but rather use a linear curve fit of test results for each PV module.
- As light intensity increases, voltage goes up logarithmically.
  As the intensity of the incident light increases (photon flux or photons/second) increases, more electron hole pairs are created, and Δn_{light} increases, thus increasing voltage in the equation. The fact that increasing light intensity also heats the cell and increases its temperature obviates this effect.

As temperature approaches absolute zero, or as the ratio of possible states occupied by light-induced electrons (the argument of the ln function) approaches 1, the voltage approaches that corresponding to the band-gap of the semiconductor material, $\varepsilon_{\text{gap}}/q$. We expect current to go up linearly with photon flux (twice as many photons create twice as many electron/hole pairs, twice the coulombs and twice the amps), but it is not obvious that voltage would go up with light intensity until one studies the equation. These observations offer two pathways to improved PV efficiency:

> Keep PV cool: PV panels should be mounted in such a way that air can circulate around them and keep them cool.
>
> Focusing or concentrating collectors offer higher efficiency: The record-high efficiencies reported for PV devices are often measured under focused sunlight. Of course, focusing also increases the temperature, which reduces efficiency and may damage the material. Cooling is required to mitigate the temperature effect and only some types of materials can tolerate the high temperatures involved so focusing is not recommended for all material types.

TIP

Electric Current: Electrons and Holes

Electric current (amps) is a measure of the electric charge (coulombs) moved per unit time (seconds). Both electrons and holes carry charge so the total current is the sum of the effects of both. The direction of current flowing from a higher voltage to a lower voltage is considered positive, but remember that electrons have a negative charge. The charge of an electron, q, has a value of 1.602×10^{19} coulombs, and an Ampere (amp) is defined as one coulomb per second. So if electrons are moving from right to left, current is moving from left to right. This sign convention sometime causes confusion when looking at electron flow and current through a PV cell.

Electric Current Flux of a PV Cell

The electric current flux, J, is the current through the cell (amps) divided by the cell cross-sectional area, A (cm^2), so $J = i/A$. Shockley discovered the relationship between current flux and voltage as the expression (Fraas and Partain 2010):

$$J = J_{\text{light}} - J_o \left\{ e^{\left[\frac{q(v+JR_{\text{series}})}{kT}\right]} - 1 \right\} \tag{3-2}$$

Where J_{light} is the current flux of both electrons and holes generated by the incident light.

We see from Equation 3-2 that J_o, the Shockley diode reverse saturation current flux including both electrons and holes, subtracts from this. This is also called the *dark current* because it is the value of current that the equation would have at zero light level. Consider this simple explanation: for each photon we get a free electron resulting in J_{light}. Some of these electrons will have sufficient energy to make it over the potential barrier caused by the imposed voltage, v, and the remainder will not. The fraction that does not make it over the barrier will recombine with holes by going back through the diode of the junction and is calculated from Fermi's distribution of energy as a function of temperature using Boltzmann's constant, which is the ratio of energy to temperature. The derivation of J_o is beyond the scope of this discussion but is described in the references. Notice that J appears on both sides of the equal sign, so this equation has to be solved by iteration: guess a value of J, see if the two sides are equal, and then adjust your guess for J until both sides are equal. R_{series} is defined in the circuit diagram below. Here we can see the first hint of a relationship between current and voltage. The effect of the voltage v is to increase the height of the potential energy barrier that an electron must have enough energy to jump over in order to contribute to the current out of the cell. As voltage increases, fewer electrons have enough energy to do this.

Simplified Circuit Model for Ideal PV Cell

The circuit model described in the references (Decher 1997) is more complicated, and includes two diodes, but I find that simplifying it still allows a description of the relationship between current, i, and voltage, v, for a PV cell. Consider the circuit diagram of a PV cell illustrated in Figure 3-4 that consists of:

- J_{light}: The p-n junction is modeled as a constant current source with current depending on the photon flux
- J_{diode}: The recombination of electrons and holes within the cell is modeled as a current through a diode which does not contribute to current output of the cell. This is the Shockley diode reverse saturation current of Equation 3-2.
- R_{series}: The electrons have to travel a long distance through the thick n-type (phosphorous) layer to get to a surface electrode, and the resistance of this is modeled as a resistance in series with the load.
- R_{shunt}: Internal shorting within the cell is modeled as current through a shunt resistance and is small. It is neglected in the references but I leave it in here for completeness.

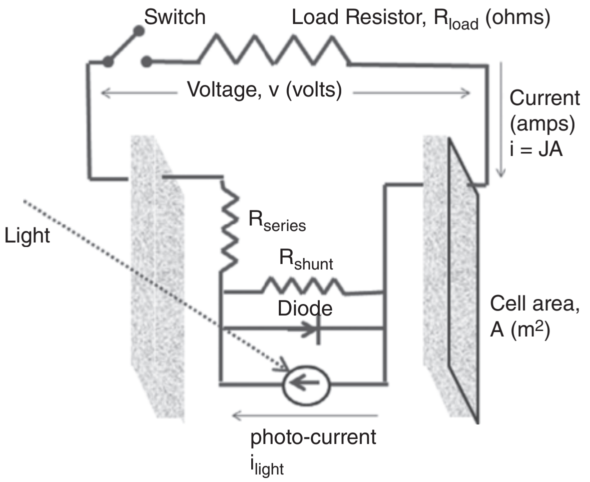


Figure 3-4. A simplified circuit diagram of a PV cell shows a diode, with series and shunt resistances connected to an external load resistance. (Figure by the author)

Currrent J is the useful current out of the cell. Here again, rather than current i we refer to current flux J, but the two are related only by the exposed area of the cell $J = i/A_{\text{cell}}$. The useful voltage, v, across the terminals would be determined by the combination of the load resistance and the resistances internal to the cell. Kirchoff's current law tells us the currents into a node must sum to zero so:

$$J = J_{\text{light}} - J_{\text{diode}} - J_{\text{shunt}} \tag{3-3}$$

Substituting Shockley's relation, equation 3-2, and expressing the shunt current as a ratio of voltage to resistance gives us the desired relationship between voltage and current of a PV cell connected to a load:

$$J = J_{\text{light}} - J_o\left\{e^{\frac{q(v+JR_{\text{series}})}{kT}} - 1\right\} - \frac{v + JR_{\text{series}}}{R_{\text{shunt}}} \tag{3-4}$$

The short circuit current, J_{SC}, is this expression, Equation, 3-4, with v equal to zero, and would thus be the maximum current for a given light level. The open circuit voltage, v_{oc}, may be determined by setting J equal to zero and represents the voltage that balances light-induced current in the internal cell resistance.

An expression for open circuit voltage as a function of current flux is

$$v_{oc} = \frac{kT}{q}\ln\left(\frac{J_{sc}}{J_o} - 1\right) \tag{3-5}$$

Where J_{sc} is the short circuit current flux (amps/cm^2) and J_o is the "dark current," the value for current density that the equation for current flux retreats to as incident light goes to zero. While it is merely a mathematical abstraction, J_o can be shown on a plot of current versus voltage if the plot is extended to current flux less than zero.

The derivative of the product of current and voltage is set to zero in order to find the condition that maximizes power output of the cell. In order to solve the resulting equation for the voltage which maximizes power output, v_{mp}, we must iterate on the value of v_{mp} until the following equation is satisfied:

$$\frac{J_{sc} - J_o}{J_o} = e\left(\frac{qv_{mp}}{kT}\right)\left[1 + \frac{qv_{mp}}{kT}\right] \tag{3-6}$$

That is to say, guess a value of v_{mp} and try larger and smaller values until both sides of Equation 3-6 are equal. The current flux that maximizes power output, J_{mp}, may also be calculated using v_{mp}.

$$J_{mp} = \frac{J_{sc} + J_o}{\left(1 + \frac{kT}{qv_{mp}}\right)} \tag{3-7}$$

Example Calculations of PV Cell Voltage and Current

Consider a PV cell with dimensions 1 cm by 1 cm. At room temperature (300 K), the dark current flux is $J_o = 2.47 \times 10^{-13}$ A/cm^2 and the short current current flux is $J_{sc} = 1.06 \times 10^{-2}$ A/cm^2. This example is to calculate the open circuit voltage and the voltage which maximizes power output. Using the information in Table 3.1, we calculate the area of the cells required to provide 240 watts of power at 24 volts.

TABLE 3.1 EXAMPLE CALCULATION OF PV CELL VOLTAGE AND CURRENT

v_{oc}:	Open circuit voltage Equation 3-6 $v_{oc} = (1.38 \times 10^{-23}$ J/K)*(300K)/(1.69 × 10^{-19} J/eV)*ln((1.06 × 10^{-2} A/cm^2)/(2.47 × 10^{-13} A/cm^2) + 1)	0.634 volts
v_{mp}:	Maximum power voltage; iterate Equation 3-7	Iteration gives 0.555V
i_{mp}:	Maximum power current flux; Equation 3-8; = ((1.06 × 10^{-2} A/cm^2) + (2.47 × 10^{-13} A/cm^2))/(1 + (1.38 × 10^{-23} J/K)*(300K)/1.69 × 10^{-19} J/ev)/(0.555V))	1.01 × 10^{-2} amps/cm^2
Cells in series:	To get to 24V put (24V)/(0.555V) = 44 cells in series	44 cells in series
Strings in parallel:	To get to 240W requires 240W/24V = 10A of current. Number of strings = 10A/(1.01 × 10^{-2} A/cm^2) = 990 strings in parallel	990 strings in parallel
Total number of cells:	990 parallel strings, each of 44 cells in series	43,560 cells
Total area:	Each cell is 1 cm × 1 cm in this example	4.36 m^2

i-v (Current-Voltage) Curve for a PV Cell or Module

The two parameters, open circuit voltage v_{oc} and short circuit current $i_{sc} = J_{sc}A$, peg the two extremes of a curve called the i-v curve. The maximum current is the short circuit current, i_{sc}, but as we start to impose a resistance (and thus a voltage) on the cell the current drops off, until the point where the load resistance is infinite (open circuit) and the voltage is at its maximum value, v_{oc}, and the current is zero. Figure 3-5 shows a typical i-v curve, which could be drawn for a PV cell, a PV module, or a whole array of PV modules. While the i-v curve for a cell may be drawn from Shockley's equation relating current and voltage in Equation 3-4 above, we practitioners refer to i-v curves measured, rather than calculated, for commercially available PV products.

Power is voltage times current, and we wish to operate the cell at the voltage and current that maximizes power output, v_{mp} and i_{sc}. The maximum power output is given the symbol P_{max}. This would be the combination that maximizes the area of the rectangle in Figure 3-5. The voltage, v, and current, i, that a cell operates at depends on the resistance of the load that it is connected to. The way to change the operating point is to change the load resistance. In Figure 3-5 we see an operating point that is not ideal because it does not maximize the power output of the device. In order to maximize power we would have to increase the load resistance so that $v = v_{mp}$. PVs are very different than other types of generators in that short circuit current is not much higher than operating current. If we short circuited a battery, it would overheat and perhaps explode due to high current. But PV current is limited to the amount of current generated by the sunlight. If we are not able to change the load resistance (say, for example, it depends on the state of charge of a battery being charged), then a DC to DC converter, called a *maximum power point tracker*, may be used to adjust the operating voltage (and current) of the PV panel to its maximum power value and deliver a different voltage to the load. As we will see, the maximum power point also depends on temperature and insolation, so such a device would continuously adjust voltage to optimize performance.

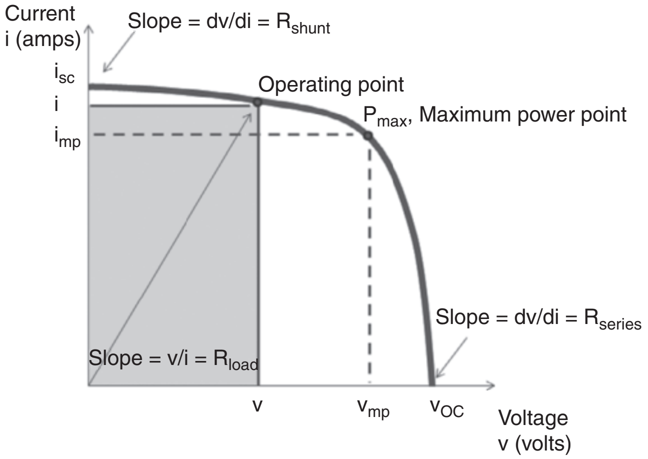


Figure 3-5. The current-voltage (i-v) curve for a photovoltaic device showing short-circuit current, open circuit voltage, maximum power point, and point corresponding to the actual operating voltage. (Figure by the author)

Series and Parallel Configuration of PV Cells within a PV Module

Each silicon PV cell of the type considered here has an open-circuit voltage of about 0.6 volts regardless of its area (with current withdrawn the voltage will be less). Voltages in series add, and currents in parallel add. So in order to generate higher, more useful, voltages, cells are wired in series with the metal contacts on the front of one cell wired to the contacts on the back of the adjacent cell. Two PV cells wired in parallel would be precisely the same as one PV cell with twice the surface area, A. Figure 3-6 shows series/parallel arrangement of cells such as those that might be found in a PV module, with the internal wires leading to terminals in the junction box of the module labeled A, B, C, and D.

There is a string of 12 cells in series for a voltage of approximately 7.2 volts between terminals A and B, and let's say

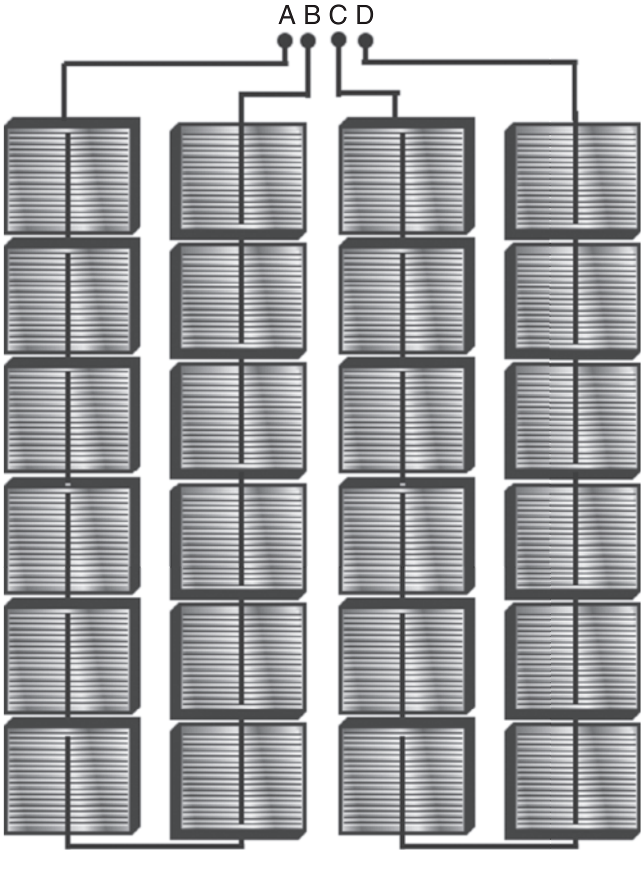


Figure 3-6. Diagram of wiring connecting cells and junction box in a PV module. For cells wired in a series string, voltage adds. For series strings connected in parallel, current adds. (Figure by the author)

the cells are of such an area, A, that they produce one amp of current. If all we needed were 7.2 volts to charge a 4 volt battery, we could wire the two strings in parallel by a jumper wire between A and C and another jumper between B and D, resulting in 2 amps of current at 7.2 volts. Now say we want to use the same PV module to charge an 8 volt battery. We could connect terminals B and C with a jumper wire and thus connect all 24 of the cells in series. This would result in a voltage of 14.4 volts and a current of 1 amp. The overall power is 14.4 watts and is the same in both arrangements, but we can get the desired voltage by the configuration of the wiring connecting the cells in the module. Some PV modules have 36 cells in series, which provides up to 20 volts to charge a 12-volt battery. Others have perhaps 72 cells in series and voltages around 50V for on-grid applications without batteries.

When PV cells are connected in series or parallel, the interdependence of voltage and current continues, so, as shown in Figure 3-7, the i-v curves stack on top of each other when cells are connected in parallel (currents add), and stack side by side when connected in series (voltages add). The desired operating point is the maximum power point for the whole series/parallel combination on the combined i-v curve.

EFFECT OF INSOLATION AND TEMPERATURE ON THE i-v CURVE

As incident solar radiation, insolation, I_C (W/m^2), increases, each additional photon creates an additional electron-hole pair and since electric current refers to the number of electrons and holes traveling around a circuit, the current goes up linearly with insolation. Twice as intense sunlight means twice as much current.

Sunlight that is not converted to electricity and exported from the module is manifest as heat and increases the temperature of the PV cells within the module. The PV cells may operate at a temperature 20°C (40°F) hotter than the ambient air temperature depending on sunlight, wind-speed, and how well air circulates around the modules. Calculation of the PV cell temperature, T_{cell}, is below in the section describing the energy balance of the PV module.

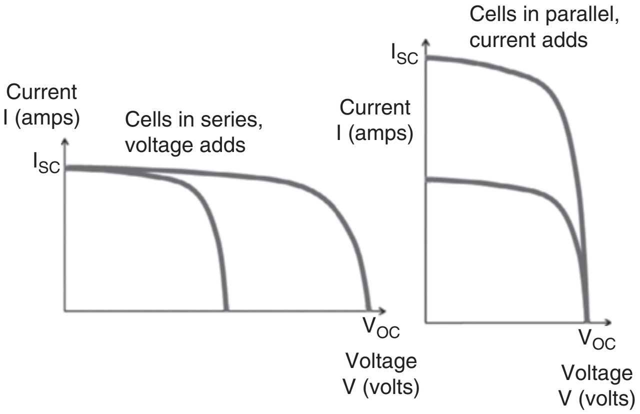


Figure 3-7. For PV cells connected in series, the voltage of the i-v curves add; for PV cells connected in parallel, current of the i-v curves add. (Figure by the author)

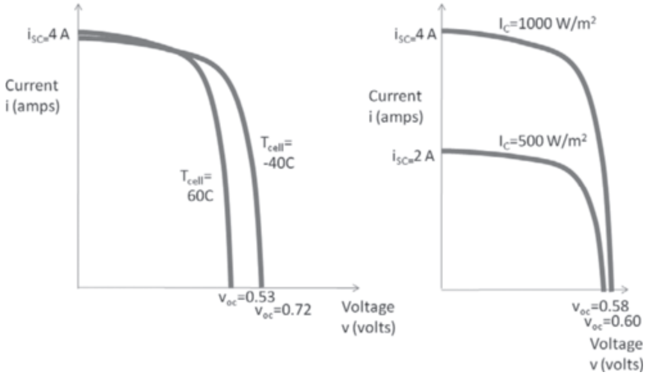


Figure 3-8. Voltage varies logarithmically with temperature, and current varies linearly with insolation as illustrated by the effects on an example i-v curve. (Figure by the author)

As the temperature increases, the voltage of a PV cell goes down according to the linear relationship of T in the Shockley equation (remember that the ln function is always negative since its argument, the ratio of the increase in the number of electrons freed by light to total electron states, is always less than unity). Current has a weak logarithmic dependence on temperature. The effect of temperature and insolation on the i-v curve is illustrated in Figure 3-8.

DEPENDENCE OF VOLTAGE AND CURRENT ON TEMPERATURE

In practice, rather than to use Shockley's relation, the temperature dependence is measured experimentally and a linear curve-fit is used to adjust the current and voltage at key points on the i-v curve measured at $T_{\text{cell}} = 25\text{C}$ to the temperature that the cell would experience in a given situation.

The coefficient measured in a test is called the *voltage temperature coefficient*, β, and may be expressed in units of volts/C, but is more often normalized by dividing by v_{oc} and, since that ratio has a lot of zeros, often in %/C ("percent per degree C"). Both open-circuit and maximum power voltage always go down with increasing temperature, so both coefficients will have a negative value.

$$\beta_{oc} = \frac{1}{v_{oc}} \frac{dv}{dT} \tag{3-8}$$

$$\beta_{mp} = \frac{1}{v_{mp}} \frac{dv}{dT} \tag{3-9}$$

$$v_{oc} = v_{oc\text{ at }25c}\,[1 + \beta_{oc}\,(T - 25C)] \tag{3-10}$$

$$v_{mp} = v_{mp\text{ at }25c}\,[1 + \beta_{mp}\,(T - 25C)] \tag{3-11}$$

As shown in (King, Kratochvi, and Boyson 1997) the relations are indeed very linear, but there is some scatter in the data. The reported coefficient is an average number. People assign importance to a difference between –0.0046 and –0.0048/C when in fact these numbers should be considered the nearly the same considering the scatter in the data. Also, temperature coefficients are larger for high module temperature (say >40C), and thus cannot be approximated linearly across a wide range of temperature. First Solar used to correctly report two coefficients in their specifications (values of –0.002/C for $T < 40$ C, and –0.0025 for $T > 40$ C), but are more recently reporting just one value.

Manufacturer's literature also reports the increase in current with temperature, α, but this is an order of magnitude less than the effect on the voltage and is often neglected. Short circuit current always goes up with temperature, so α_{sc} has a positive value, but because of the shape of the i-v curve, current at the maximum power point may go up or down, or stay nearly the same.

$$\alpha_{sc} = \frac{1}{i_{sc}}\left(\frac{di_{sc}}{dT}\right) \tag{3-12}$$

$$\alpha_{mp} = \frac{1}{i_{mp}}\left(\frac{di_{mp}}{dT}\right) \tag{3-13}$$

$$i_{sc} = i_{sc\ at\ 25c}\,[1 + \alpha_{sc}\,(T - 25C)] \tag{3-14}$$

$$i_{mp} = i_{mp\ at\ 25c}\,[1 + \alpha_{mp}\,(T - 25C)] \tag{3-15}$$

Since the dependencies of current and voltage on temperature differ, the best way to account for them is with a "map" that lists a specific value of current and voltage at each temperature and sunlight condition. However, PV manufacturer's literature takes a simpler approach as lists a power temperature coefficient, δ_{mp}, which is the approximate rate at which the power reduces with increasing temperature and is also reported in units of 1/C or %/C.

$$P_{mp} = P_{mp\ at\ 25c}[1 + \delta_{mp}(T - 25C)] \tag{3-16}$$

Power is the product of current and voltage, so the product-rule in calculus applies.

$$\delta_{mp} = \frac{1}{P_{mp}}\frac{dP_{mp}}{dT} = \frac{1}{v_{mp}i_{mp}}\frac{d(v_{mp}i_{mp})}{dT}$$
$$= \frac{1}{i_{mp}}\frac{di_{mp}}{dT} + \frac{1}{v_{mp}}\frac{dv_{mp}}{dT} = \alpha_{mp} + \beta_{mp} \tag{3-17}$$

Without specifying a power coefficient, power at a temperature other than the reference temperature may be expressed as the product of adjusted current and adjusted voltage. Note that this would incur some small error, since the voltage coefficient is evaluated only at the reference insolation (and thus the current associated with the reference insolation).

$$P_{mp} = V_{mp\ at\ 25c}[1 + \beta_{mp}(T - 25C)] * i_{mp\ at\ 25C}[1 + \alpha_{mp}(T - 25C)] \tag{3-18}$$

The reduction in PV output with temperature is due largely to the lower voltage, but the power temperature coefficient may be higher or lower than the voltage coefficient depending on the current coefficient. For example, a module might have a voltage temperature coefficient of –0.004/C; a current temperature coefficient of –0.001/C; and a power temperature coefficient of –0.005/C.

See the numerical example regarding how these factors are applied. The temperature correction factors depend on the type of PV device *(on the band gap)*, as discussed below in the context of different types of PV, but may be different for makes and models within a type as well. In general, crystalline silicon has the highest power output at low temperatures, but the power drops off with temperature more rapidly than other types. Temperature has less of an effect on the power output of amorphous silicon than it does on other types of PV because the voltage doesn't go down as much with increasing temperature and the current goes up, especially at low insolation levels. Cadmium telluride also maintains power output at higher temperatures.

Example Calculation of the Effect of Temperature on Voltage and Power

Consider a crystalline silicon PV module with a rated power of 180W; an open circuit voltage of 43.6V; a maximum power voltage of 35.8V; and a maximum power current of 5.03A, all measured under "standard test conditions" that maintain the cell temperature at 25C (Table 3-2). According to the manufacturer's literature, the voltage temperature coefficient reported from the testing is $\beta_{mp} = -0.0040$/C; the current temperature coefficient is $\alpha_{mp} = 0.0001$/C, and the power temperature coefficient is $\delta_{mp} = -0.0050$/C. In more realistic conditions (heated by the sun), the cell temperature rises to 47C. Calculate the open circuit voltage, and the voltage, current, and power output at the maximum power point at this higher cell temperature using both the power temperature coefficient δ and the product of adjusted voltage and adjusted current.

We see in this example that the power output of the module at 47C (116F) is about 20W, or about 10 percent, less than the rated power at 25C (77F) cell temperature. On hot days the cell temperature would be hotter than 47C and the output even lower than this. Use of the power temperature coefficient provides a slightly lower answer than if we adjust voltage and current and take the product of those two to estimate power.

Example Calculation of Voltage at Very Low Temperatures

Consider a crystalline silicon PV module with an open circuit voltage of 43.6V measured under standard test conditions

TABLE 3-2. EXAMPLE OF CORRECTING PV MODULE VOLTAGE, CURRENT, AND POWER PARAMETERS FOR TEMPERATURE OTHER THAN THE RATING CONDITIONS

Rating conditions			
T_{cell}	Cell temperature	25 C	(77F)
v_{oc}	Open circuit voltage	43.6V	
v_{mp}	Max power voltage	35.8V	
i_{mp}	Max power current	5.03A	
P_{mp}	Rated power	180 W	
Actual conditions			
T_{cell}	Cell temperature	47 C	(117F)
v_{oc}	Open circuit voltage (Equation 3-9)	v_{oc} = 43.6V*[1 – (0.0040/C)*(47C – 25C)] =	39.8V
v_{mp}	Max power voltage (Equation 3-10)	v_{mp} = 35.8V*[1 – (0.0040/C)*(47C – 25C)] =	32.6V
i_{mp}	max power current (Equation 3-15)	i_{mp} = 5.03A*[1 – (0.0001/C)*(47C – 25C) =	5.02A
P_{mp}	Rated power, based on power temperature coefficient (Equation 3-16)	P_{mp} = 180*[1 – (0.5%/C)/100%* (47C – 25C) =	160.2W
P_{mp}	Rated power, based on product of voltage and current (Equation 3-18)	P_{mp} = 35.8V*[1 – (0.0040/C)*(47C – 25C)]* 5.03A*[1 – (0.0001/C)*(47C – 25C)] =	163.8W

TABLE 3-3. EXAMPLE CALCULATION OF THE MAXIMUM NUMBER OF MODULES IN SERIES THAT OBSERVES THE 600V LIMIT OF UL LISTING

Rating conditions			
T_{cell}	**cell temperature**	25 C	(77F)
v_{oc}	**open circuit voltage**	43.6V	
Actual conditions			
T_{cell}	**cell temperature**	–10 C	(117F)
v_{oc}	**open circuit voltage Equation 3-9**	V_{oc} = 43.6V* [1 – (0.0040/C)* (47C – (–10C))] =	51.5V
N_{series}	**number of modules in series**	$N_{series\ mp}$ = (600V)/(51.5V) = 11.6	11 modules

which maintain the cell temperature at 25C (Table 3-3). At this voltage we could connect 13 modules together in series without violating $600V_{dc}$ limit imposed by the safety listing of the module (UL listing). According to the manufacturer's literature, the voltage temperature coefficient reported from the testing is β_{mp} = –0.0040/C. How many of these modules could be connected in series without violating the $600V_{dc}$ limit if the coldest temperature expected at the site is –10C based on historic weather records?

WARNING

Warning about High Voltage at Very Cold Temperatures

The maximum voltage for most PV modules, as well as wire, disconnects, and other components in a PV system, is limited to a maximum voltage, typically 600V DC or 1000 V DC depending on the jurisdiction and the applicable standards ($600V_{dc}$ in the USA). This limit results from the integrity of the electrical insulation on the PV modules but also on the wire and other electrical components. Since the voltage of a PV module goes up as temperature goes down, it is important to calculate the voltage that an array of PV modules in series generates under the coldest possible daytime temperature at a location. This record-low temperature may often be found in the weather data for a site, and then the voltage reported for the modules in the manufacturer's literature may be corrected from the rating cell temperature of 25 °C (77 °F) to the cell temperature corresponding to the record-low temperature for the site using the voltage temperature correction factor, which is also reported in the manufacturer's literature for the PV modules.

Rather than calculate the cell temperature as a function of insolation, we make the conservative assumption that it could be as cold as the record low ambient temperature, which would occur if the sun quickly came out from behind a cloud.

We see in this example that if we looked only at open circuit voltage at the standard rating conditions, 13 modules in series would experience a voltage over 100 V greater than allowable under record cold conditions. Thus, in the design of a PV array, the voltage must be calculated at the lowest temperature expected at a site, and that corrected voltage must be used to configure the array to observe maximum voltage limits. In this example, only 11 modules could be connected in series.

Efficiency of a PV Module

We see from the discussion above that the power output of a PV module depends on the resistance of the load and the resulting operating point on the i-v curve, resulting in a value between zero (for open circuit or short circuit condition) to the maximum value of P_{mp}. The reported efficiency of a PV module is this maximum power divided by the incident solar insolation and the area of the module, A_c where the c subscript denotes "collector" to generalize with other types of solar collectors. By convention, this area includes the total frontal area of the module including the inactive area between cells and the frame.

$$\eta = \frac{P_{mp}}{I_C A_C} \tag{3-19}$$

PV modules on the market today have efficiencies as low as 6 and as high as 22 percent. Those used where efficiency is a premium, such as space vehicles, have efficiencies in excess of 40 percent. Such efficiencies are already comparable to other energy conversion devices in use today (diesel generators, gas turbines, etc.), and researchers continue to improve PV efficiency each year.

One may wonder why efficiency is important if the sunlight is free. But looking at Equation 3-19, we see that for a given amount of power, P_{mp}, a device with half the efficiency would require twice the area, A_C, resulting in twice the rack, twice the conductor, twice the conduit, twice the foundation, and twice the installation labor. Based on the just the cost of the PV module the less efficient device is cheaper, but when we consider the total system cost we realize the benefit of a high efficiency.

The maximum possible efficiency of a PV device depends on the type of device. In 1961, Shockley published a paper using the second law of thermodynamics (radiation balance between two blackbodies- the sun and the PV cell) to calculate the maximum efficiency of a solar energy converter with a single p-n junction to be 30 percent (Shockley and Queisser 1961). But this is for only one junction. This limit has already been exceeded by using multiple junctions formed by different materials in the same device. These authors also considered that one photon could produce only one electron, but strategies to improve efficiency include using photon energy in excess of the electron band gap to contribute energy to free a second electron. The theoretical maximum efficiency of any PV device based on the second law of thermodynamics is 86 percent. Wouldn't that be remarkable if we could convert that fraction of any resource into useful electricity?...especially a resource as free and environmentally friendly as sunlight? Photovoltaics that are more efficient than heat engines (such as those found in today's power plants) are already commercially available, and are not even near their theoretical maximum efficiency yet.

DIFFE.RENT TYPES OF PHOTOVOLTAIC DEVICES

The discussion above regarding how PV works involves a single crystal structure of silicon. But it is also possible to fabricate a photovoltaic device by depositing thin layers, also called thin films, of p-type and n-type semiconductors on a glass, metal or plastic substrate through the processes of chemical vapor deposition or epitaxy. Silicon has 14 electrons (4 valence electrons), which puts it in the column labeled 14 in the periodic table of the elements. Silicon-based products represent 90 percent of the PV market, over 15 GW, in 2011, including single crystal, multi-crystal, and thin film devices (NREL 2011). Germanium is also in column 14 and is a natural semiconductor used in PV devices. Elements from column 13 (such as gallium and indium) may be combined with elements from column 15 (such as arsenic) to produce a photovoltaic effect. Such PV types are called III-V devices, because before 1990 the columns of the periodic table were labeled with roman numerals corresponding to the number of valence electrons. Cadmium in column 12 is combined with tellurium in column 16; and copper in 11, indium and gallium in 13, and selenium in 16 are also combined to make PV devices (Dayah 1997). It's very interesting to me that all these are symmetrical around column 14—but the physical explanation for that eludes me.

The thin film technologies advanced in the market in 2007 and 2008, when prices for refined silicon were high, but refinery capacity has increased and crystalline technologies are again dominant in terms of cost and performance. Figure 3-9 shows how technology development has improved the efficiency of all types of PV devices since 1975. Silicon crystal and gallium arsenide single-crystal devices are already approaching their theoretical maximum, but other types show improvement in recent years and new emerging types show considerable room for improvement. All the technologies have opportunities for price reduction.

In the following sections we examine the operating principle, manufacturing considerations, measured efficiency, and cost implications of the various types of PV. We also mention companies manufacturing certain types, but keep in mind that such lists are not inclusive-companies go in and out of business all the time—especially solar companies. But the industry as a whole has enjoyed tremendous growth rates, driven in part by advances in device and manufacturing technology. Also, when reading the discussion of costs, keep in mind that all types sell into a market where $/watt is the primary pricing metric, so, regardless of what it costs a manufacturer to produce a module, the selling price may get depressed or propped up by market pricing.

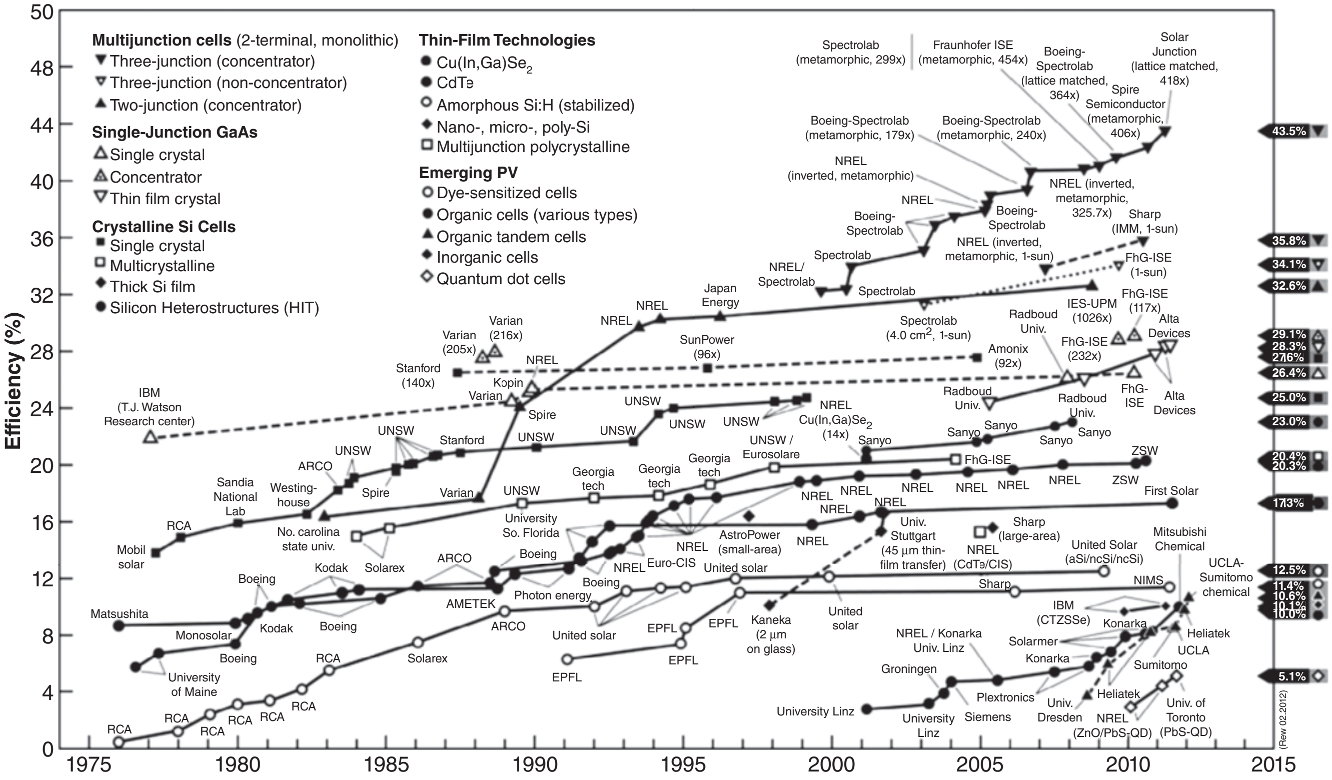


Figure 3-9. This chart of maximum efficiency of laboratory research PV cells of different types reported by NREL shows continued improvement in efficiency from 1975 to 2012. (Reprinted with permission by the National Renewable Energy Laboratory

Single Crystal Silicon (c-Si)

The earliest PV concept derived from solid-state diodes involving single crystals of silicon, grown in a process invented by Polish scientist Jan Czochralski in 1916. A crystal is grown by introducing a seed crystal on the end of a rod into a crucible of molten silicon at a temperature where solid and liquid phases are in equilibrium (1,414 °C, 2,577 °F). The seed is rotated and if it is withdrawn from the melt at a slow enough rate, the diameter increases so that a cone of solidifying crystalline silicon grows beneath it. The cone grows in diameter until the cross-sectional area is sufficient to generate the number of amps of electric current required of the cell, usually 10 to 20 cm, although efforts to make diameters up to 45 cm are underway (Intel 2008). Then it is withdrawn at a faster rate that keeps the diameter constant, and it forms a cylinder. When the single crystal is the desired length, the rate of withdrawal is increased and an inverted cone forms on the other end. This second cone is needed to avoid "dislocations," or imperfections in the crystal. The cones are cut off and recycled, leaving a cylinder called a boule. The crystal-growing process is energy-intensive and takes a lot of time—about a day for a 1-m (3-foot) long boule.

The boule is cut into wafers only a few tenths of a millimeter thick (0.008 inch) with wire saws entraining an abrasive slurry. Since the wire is about the same diameter as the desired wafer thickness, about half the material is lost as "kerf" (sawdust). The silicon material must be of semiconductor purity (rather than metallurgical purity) because even a few parts per million of impurities would undermine the PV effect. You would think the sawdust would be recycled into the melt, but because it's been mixed with the abrasive slurry it is not, making this an expensive loss. Usually the p-type dopant is added to the mix before the crystal is grown, the n-type dopant is then diffused into the top surface of a wafer by masking the back of the wafer and baking it in an oven with the n-type material on the top. The top surface is etched to expose the pyramid structure formed by the angle between the silicon atoms in the crystal, which provides an efficient coupling with the incoming light. The wafer is round, and some PV modules have round or half-round cells with inactive space between them. But to pack more active area into the module frame, the round edges are often cut off resulting in a nearly square wafer. An antireflective coating of silicon nitride is deposited on the surface by chemical vapor deposition, and this material has the added benefit of combining with and thus "passivating" unbound electrons which otherwise absorb photon unproductively. Electrical contacts are created by screen printing and sintering silver or aluminum in the shape of fine wires on the top surface and a continuous full-area sheet on the back side.

The earliest type of products, single crystal PV (also called "mono-crystal" PV), are still prevalent in the market and offer efficiencies of around 14 to 23 percent, much higher than lower-cost alternatives. The highest efficiency reported for a single crystal cell in the laboratory is 25 percent by University of New South Wales and 27.6 percent under sunlight focused to 96 × 1sun by Amonix (Amonix 2005). Single crystal PV devices are manufactured by SunPower, Shell Solar, and other companies. Predictions that crystal silicon modules could not be manufactured for less than $1/W proved to be untrue, as Chinese suppliers do sell at or below that price point, although many other companies have gone out of business due to competition from lower-cost thin film technologies. In 2011, crystal or multicrystal PV represented 80 percent of the world market. Reported characteristics of some commercially manufactured crystalline PV modules are listed here (Razykov et al. 2011):

- SunPower 315: 19.3 percent efficient; 0.673V open circuit voltage; –0.0038/C power temperature coefficient
- Suniva Opt260: 16.2 percent efficient; 0.637 V; –0.0046/C power temperature coefficient
- BP 4180T: 14.4 percent efficient; 0.606V open circuit voltage; –0.005/C power temperature coefficient
- Suntech STP 180S: 14.1 percent efficient; 0.622V open circuit voltage; –0.0048/C power temperature coefficient
- Sharp U-175: 14.1% efficient; 0.617 open circuit voltage; –0.00485/C power temperature coefficient
- SolarWorld 230: 13.7 percent efficient; 0.617 open circuit voltage; –0.0033/C power temperature coefficient

Multicrystal Silicon (mc-SI)

Instead of growing a single crystal in the Czochralski process, silicon may be melted, or molten silicon poured into, a rectangular crucible and cooled from the bottom slowly, in such a way that large grains (each a single crystal) grow vertically upwards within the volume of the material. These cells are called *multicrystal* or *polycrystal* cells. The other processing steps are essentially the same as those described for single crystal above. Although avoiding the considerable time and cost to grow a single crystal, each of the boundaries between grains represents a resistance to electron flow and a site where holes and electrons can recombine without producing useful electricity. So the efficiency of multicrystal PV is around 13 to 17 percent, which is 4 to 6 percent less than the single crystal version. The highest reported efficiency for a multicrystal cell in the laboratory is 20.4 percent (Fraunhofer Institute 2004). Still, due to the lower cost, PV panels made with this technology are very competitive in applications where efficiency is not the priority.

As mentioned above, grain boundaries degrade performance so very large grain sizes have an advantage. However, on the scale of very small dimension crystals the energy levels are more exact, which may improve performance. So development of “nanocrystalline” and “microcrystalline” polycrystalline silicon solar cells with very small crystal structures is also underway.

Multicrystal PV modules are manufactured by Kyocera, BP Solar, and many other companies. Reported characteristics of some commercially manufactured multicrystalline PV modules are listed here (Razykov et al. 2011):

- Q-Cells QPro215: 15.0 percent efficient; 0.629 V open circuit voltageFIX minus; –0.0045/C power temperature coefficient
- Suntech STP190S: 14.9 percent efficient; 0.625V open circuit voltage; –0.0045/C power temperature coefficient
- Kyocera KD240: 14.9 percent efficient; 0.615V open circuit voltage; –0.0046/C power temperature coefficient
- BP 320N: 13.8 percent efficient; 0.607V open circuit voltage; –0.0050 /C power temperature coefficient
- Sharp ND-224-UC1: 13.7 percent efficient; 0.610V open circuit voltage; –0.00485/C power temperature coefficient
- Trina Solar TSM-245-PO 05.08: 15% efficient; 0.6V open circuit voltage;–0.0043/C power temperature coefficient.

In the last year costs have come down and in conversations with project contacts I have heard as low as $0.87 per watt for multicrystalline PV modules manufactured in China.

Silicon Film-Grown or Ribbon-Grown Silicon Crystals

Cutting either crystal boules or multi-crystal ingots with wire saws is also an expensive and time-consuming process. Hundreds of wafers are cut at one time by the wire wrapped hundreds of times around the boule or ingot, but it takes about a day for the wires to saw through the material, depending on the dimensions. The abrasives used (SiC or diamond) may also be expensive and the process of cleaning and smoothing the surface of the wafers following sawing adds processing steps.

To avoid the sawing process, silicon crystals are also grown in the shape of ribbons or films between two dendrites or wires, or drawn through dies of the desired shape. The ribbon cools rapidly and the process can be very fast compared to the process of growing crystals in a solid volume. The flat shape of a ribbon is already in the form of a wafer, and the subsequent processing steps are similar to those described above for crystalline silicon.

These ribbon products have efficiencies of 11 to 14 percent and have been manufactured by Evergreen and RWE Schott. The highest efficiency for string ribbon silicon wafers is 17.8 percent in a laboratory at Georgia Tech (Kim et al. 2003. An example of a commercially manufactured PV module using ribbon grown cells was the Evergreen ES210, which had 13.4 percent efficiency and temperature coefficient of –0.0045/C (Razykov et al. 2011).

Definition

Definition of Multijunction PV Devices

Photons of the solar spectrum can generate a lot of current (large number of electrons) in low-band-gap materials, but at a low voltage. In high band-gap materials, fewer photons will free electrons (low current), but they will be at a higher voltage. The idea behind multijunction devices is that they absorb each color of the solar spectrum with a different material that has a band gap equal or close to the photon's energy. By stacking cells with the highest band gap at the top, each photon is absorbed by the layer that can use it most effectively.

Each element has a specific band gap, but by combining elements in alloys, any band gap from around 0.25 eV to around 2.5 eV is possible. The theoretical maximum efficiency is 40.6 percent for a single junction with 1.6 eV band gap; 55.6 percent efficiency for two junctions of 1.63 and 0.74 eV band gap; 63.6 percent efficiency for three junctions of 2.02, 1.21, and 0.59 eV band gaps; 68.5 percent efficiency for four junctions of 2.31, 1.55, 0.99, and 0.50 eV band gaps (Razykov et al. 2011). As the number of junctions approaches infinity, a theoretical maximum efficiency is 86 percent under concentrated sunlight (De Vos 1980). Since the layers are in series, one area of research is to achieve the same current (same number of electrons, which relates to the number of incident photons at each wavelength) in each layer.

Amorphous Silicon Thin-Film (a-Si)

In crystalline silicon each atom is sharing its four valence electrons with four neighbors by covalent bonds. Rather than growing a single crystal, amorphous silicon is deposited in a very thin layer (about 1 percent of the thickness of the crystal wafers described above), on a glass, stainless steel, or plastic substrate by the process of chemical vapor deposition. Here, rather than sharing with four neighbors, an atom may share its valence electrons with only two or three neighbors, leaving unbound valence electrons called "dangling bonds." These dangling bonds absorb photons and dissipate their energy as heat unproductively, but they can be "passivated" by adding hydrogen, which is one electron and one proton, and which forms a covalent bond with each free electron. Amorphous silicon doped with n-type and p-type dopants can thus form a PV device, albeit at a much lower efficiency than crystal PV cells. In order to get a useful efficiency, the p-type and n-type layers must be separated by an "intrinsic" layer, which is silicon free of either n-type or p-type dopants. Despite the low efficiency, amorphous silicon has some other advantages which make PV products made from this material competitive in the market place:

1. It avoids the time and cost of growing a crystal and uses less than 1 percent of the expensive electronics-grade silicon of crystalline cells
2. Multiple thin layers can be built up on top of each other, and may be tuned to different parts of the solar spectrum, improving device efficiency considerably. For example, the Uni-Solar product had three stacked cells to use three parts of the solar spectrum.
3. Low-temperature fabrication steps allow the use of plastic as a substrate.
4. The thin film may be bent without breakage, allowing for roll-to-roll manufacturing and use on flexible mounting such as membrane roofing.
5. The thin products are very light weight, allowing use on roofs which are already near their structural capacity.
6. The efficiency is less sensitive to temperature, making them suitable for flat mounting on a roof where air cannot circulate behind them, in warmer climates, and in applications where the solar panel is producing both electricity and hot water.

Some of the first commercial PV cells were manufactured by RCA using this technology in the early 1970s and used in low power applications such as calculators. Amorphous silicon thin film products have efficiencies around 5 to 11 percent and have been manufactured by ENN Solar, Moser Baer, Sharp, Sunfilm, SunWell and Unisolar, Applied Materials, and others. Uni-solar announced 12.5 percent efficiency for an amorphous silicon cell in the laboratory (Uni-Solar 2010, 2011) but has since gone out of business. Reported characteristics of commercially manufactured amorphous silicon PV modules are listed here (Razykov et al. 2011):

- Sunfilm Q120; 8.4 percent efficient; –0.003/C temperature coefficient
- Mitsubishi MT130; 8.3 percent efficient; –0.0028/C temperature coefficient
- Uni-Solar PVL144: 6.7 percent efficient; –0.0021/C temperature coefficient
- Kaneka T-SC-120: 6.3 percent efficient;
- Bosch T90: 6.2 percent efficient; –0.0021/C temperature coefficient
- EPV 5x56W: 6.0 percent efficient; –0.0019/C temperature coefficient

Nano (nc-Si) or Micro (μc) Crystalline Polysilicon

These materials have crystals that are too small to be called multicrystal but too large to be called amorphous—they exhibit some characteristics of amorphous silicon and other characteristics of crystalline silicon. The nanoscale crystals improve electron mobility in the crystal, and improve absorption of longer-wavelength sunlight. These materials have another advantage in that they can use manufacturing techniques derived from those associated with amorphous silicon, which can occur faster and at a lower temperature than those related to manufacture of crystal cells (Carabe and Gandia 2004). Uni-solar announced a record 16.3 percent efficiency for an amorphous silicon cell in the laboratory, attributing the high efficiency to a nanocrystalline structure (Uni-Solar 2011).

Silicon Heterostructures (HIT)

HIT stands for heterostructure intrinsic thin-layer. Crystalline cells are the same material crystal through the depth of the cell (homostructures), whereas in HIT cells, different materials are involved, thus the term "hetero." Sanyo began researching this approach in 1990 and introduced product in 1997. An HIT cell starts with a wafer of n-type silicon, produced as described above, but then a very thin layer of intrinsic silicon is deposited (by chemical vapor deposition) on one or both sides and then a layer of p-type on top of that. Fabrication of these devices occurs faster and at a lower temperature than diffusing the p-type into the surface which should reduce cost. Sanyo has achieved an efficiency of 22.3 percent in laboratory cells and efficiencies of 17.8 to 20.2 percent in production PV modules (Sanyo 2007). Reported characteristics of the commercially manufactured HIT PV module are (Razykov et al. 2011): Sanyo HIP-215: 17.4 percent efficient; 0.717V open circuit voltage; –0.0030/C power temperature coefficient.

Single Crystal Gallium Arsenide (GaAs)

Gallium Arsenide is a compound semiconductor made with gallium and arsenic. GaAs is called a III-V device, because it uses materials with three and five valence electrons, in contrast to silicon's four. The resulting band-gap of 1.42 eV is a very good fit to the solar spectrum. GaAs has higher electron mobility than silicon and absorbs sunlight better, so may be thinner than silicon. GaAs is also resistant to high temperatures, making it a candidate for focusing (concentrating) solar collectors. The voltage degrades with temperature at a rate of –0.002 V/K (Luque and Hegedus 2011). Because of its thin construction (light weight, flexible), high efficiency, and resistance to radiation damage, GaAs has found application in space-based solar arrays. Collectors manufactured by Alta Devices in Santa Clara CA have achieved 23.5 percent efficiency in independent tests of PV modules and 28.2 percent efficiency in laboratory cells, which is approaching the theoretical maximum for such devices (Alta Devices 2012). The company's explanation for this high efficiency involves harvesting not only external light coming into the cell, but also photons emitted within the cell itself. Reported characteristics of another commercially manufactured GaAs device are (Luque and Hegedus 2011), where voltage and temperature coefficient are for the material type, not the specific product: ENTECH GaAs: 27.8 percent efficient under 216 suns concentration; 1.05V open circuit voltage; –0.0019/C power temperature coefficient.

Multijunction (GaAs; GaInP; Ge)

The record for the highest efficiency of any type of PV device is held by multijunction III-IV devices. Stacking multiple devices on top of each other involves matching the current density from layer to layer and also the physical characteristics of the atomic structure ("lattice matching"). Materials which fit together nicely in both respects are GaAs, gallium indium phosphide (GaInP), and germanium (Ge). These have different band gaps to harvest three parts of the solar spectrum, but have a similar lattice constant which facilitates the layers being grown on each other by a process called molecular beam epitaxy. GaAs with a band gap of 1.42 eV uses wavelengths near the peak of the visible spectrum, GaInP with a band gap of 1.85 uses the ultraviolet, and Ge with a band gap of 0.67 eV harvests the infrared part of the spectrum. The germanium generates a lot of electrons, but at too low a voltage to be useful—the other layers boost the voltage associated with each electron. The three devices are stacked in such a way that the current is the same through each layer and voltage adds, and the resulting cell voltage is around 2.8V under one sun but increases to a peak of about 3.2 V (the sum of the band gaps independently is 3.94 eV) under concentration of 326 suns. Due to the high cost of materials and manufacturing techniques, these cells are used in space-based applications where efficiency is at a premium, but because of good resistance to high temperature and a low coefficient of degradation with temperature (–0.0045 V/K), they are candidates for focusing collectors here on earth (Luque and Hegedus 2011). A dozen companies have the capability to fabricate these cells. A company named Solar Junction manufactures cells in excess of 40 percent efficiency for terrestrial focusing applications, and 43.5 percent for research cells, under 418 suns concentration (Solar Junction 2011). Sharp, an innovator in many different types of PV, reports 35.8 percent efficiency for this type of device under 1 sun (1 kW/m^2, no concentration) (Sharp 2009).

Reported characteristics of some other commercially manufactured multijunction III-V devices are listed here (Luque and Hegedus 2011). Voltage and temperature coefficients are for the material type, not the specific product:

- Spectrolab GaInP/GaInAs/Ge: 40.7 efficient under 240 suns concentration; 3.08V open circuit voltage; –0.0015/C power temperature coefficient
- Boeing GaAs/GaSb: 32.6 percent efficient under 100 suns concentration
- Amonix GaInP/GaAs/Si; 27.6 percent efficient under 92 suns concentration

Copper Indium Gallium Di-Selenide (CIGS)

CIGS is a mixture of copper indium selenide and copper gallium selenide. The band gap can vary from 1.0 eV for purer copper indium selenide to 1.7 eV for pure copper gallium selenide. CIGS lends itself to a simple manufacturing that is based more on chemical processes than the chemical vapor deposition or epitaxy used for other types of PV. The material can be laid down on a substrate through a printing or spin-coating process and then sintered (Nanosolar 2011) or may be deposited in an electroplating process. The wide variety of ways in which CIGS absorber layer can be deposited complicates development efforts (von Roedern and Ullal 2007). CIGS is very effective at absorbing sunlight, so the layer can be very thin and installed on a flexible substrate. In manufacture, the p-type CIGS layer is deposited on a molybdenum (Mo) substrate and separated from an n-type layer of zinc oxide doped with aluminum by a layer of cadmium sulphide. A transparent conducting later of zinc oxide (ZnO) protects the assembly from the elements but allows light to pass through. CIGS products have module efficiencies of around 9 to 14 percent and are manufactured by Ascent Solar, Daystar, Global Solar, Heliovolt, MiaSole, Nanosolar, Solibro, SoloPower in the US; Wurth Solar and Sulfurcell in Germany; Honda and Showa Shell in Japan; and others. The highest efficiency of a CIGS cell measured in the laboratory is 20.3 percent (ITUSolar 2012). Reported characteristics of some commercially manufactured CIS and CIGS PV modules are listed here (Razykovet al. 2011):

- WurthSolar WSGOO25 (CIS); 11.0 percent efficient; –0.0036/C power temperature coefficient
- Q-Cells (Solibro) UF-90: 12.0 percent efficient; –0.0038/C power temperature coefficient
- Avancis 130W: 11.9 percent efficient; –0.0045/C power temperature coefficient
- Solar Frontier SF85-US-B: 10.7 percent efficient; –0.0035/C power temperature coefficient

Cadmium Telluride (CdTe)

Cadmium telluride is a p-type semiconductor with a band gap of 1.45 eV, which is nearly ideal for solar collection. It also absorbs solar radiation very effectively, so it can be very thin. A CdTe PV module may be manufactured by first depositing a layer of transparent conducting oxide on glass, then a layer of n-type cadmium sulfide (CdS), then the p-type CdTe, then the back metal contact. Light passes through the glass, the TCO layer, and the n-type layer to create electron hole pairs in the p-type CdTe material. There are many processes by which the CdTe layer may be deposited, but high temperature processing limits the choice of other materials and must be done before the metal back contact is deposited. CdTe does not couple well electrically with the metal back contact, and a "buffering" layer helps make the contact. Problems with long-term stability of this buffering layer were solved in order to make CdTe products reliable over long lifetimes.

There are concerns about the toxicity of cadmium and certainly all steps must be taken to mitigate emissions and occupational hazards in the refining of the raw material and in fabrication of the PV modules. But once encapsulated in the module the chance of the cadmium being released through physical damage to a module or fire is said to be minimal. In fact, more human exposure to cadmium results from the combustion of fuels per unit of energy delivery than results from PV (Razykov et al. 2011). Cadmium is not rare, but it is produced only as a by-product of smelting other metals, mainly zinc (UCGS 2002). Thus the supply is limited by the production of these other metals. While I was meeting with a solar investor in Washington, DC, the owner of a producer in Canada landed his plane en route to Florida to have lunch with us. He said he was providing 500 tons/year for the solar industry, and at maximum he could deliver 700. Telluride is as rare as platinum, and is also toxic. Still, given that the CdTe devices can be made very thin and use very little material, the CdTe solar market is not expected to be limited by a shortage of materials if the devices can be manufactured using less of the raw material and if processes to recover Te from other manufacturing processes can be made more efficient (Zwiebel 2010). Abound Solar (recently out of business), and others as well, set up a third-party escrow fund to ensure that the cadmium and tellurium from each module sold can be recycled cradle-to-cradle at the end of the products life (Abound Solar 2012).

Cadmium telluride products have efficiencies around 8 to 14 percent and are manufactured by Abound Solar, First Solar, GE, and others. The highest efficiency for a CdTe device is in the laboratory is 17.3 percent by First Solar. First Solar began developing CdTe devices as Solar Cells Inc. in 1991 and began producing modules for $2.94/W in 2004. By 2007 the price had dropped to $1.25/W; and by 2011 the production cost of CdTe was $0.76/W (von Roedern and Ullal 2007). Reported characteristics of some commercially manufactured CdTe PV modules are listed here (Razykov et al. 2011):

- FirstSolar FS-380: 11.1 percent efficient; 0.773V open circuit voltage; –0.0020/C power temperature coefficient
- Calyxo CX55: 9.0 percent efficient; –0.0025/C power temperature coefficient
- Abound Solar AB2: 12.5 percent efficient; –0.0019/C power temperature coefficient

Dye Sensitized Solar Cells (DSSC)

I used to go hiking a lot with Jao Van de Lagemaat, who described his research on dye sensitized solar cells as "kitchen table chemistry." He was probably oversimplifying in favor of more walking and less talking, but the assembly processes are simpler than those of other types of PV discussed above. Also, DSSC devices use low-cost materials yet have achieved reasonable efficiencies, and are thus indicated as a possible path toward large-scale implementation of PV. Metal oxides such as titanium dioxide (TiO_2) and zinc oxide (ZnO) have large bandgaps suitable for generation of useful voltage, but they do not absorb sunlight. The idea behind DSSC devices is to "sensitize" these materials with dye. This idea has been involved in photography for over 100 years, but was not suitable for solar cells because the dyes only absorbed some wavelengths of sunlight and the metal oxides used could not absorb enough dye. Construction of a DSSC begins with a layer of transparent conductor on glass. Onto the transparent conductor is deposited the metal oxide, then the dye, then a redox electrolyte, then finally the back electrode. Iodine is an example of a suitable electrolyte.

Light absorbed in the dye excites an electron and transfers it to the conduction band of the metal oxide. The free electron travels through the layer of TiO2 to the transparent conductor to come out and do some useful work for us. The term "redox" refers to the gain of an electron (reduction), and then the loss of an electron (oxidation). By losing an electron the dye was "oxidized." The **oxi**dized dye is then "**red**uced" by an electron from an electrolyte ion, restoring the dye to its original state. The electrolyte, in turn, is reduced by an electron coming from the electrode on the back of the cell. Thus the circuit is completed, each material is restored to its original state, and the process can continue without permanent chemical change.

In 1991, Gratzel and colleagues used TiO_2 nanoparticles which have a lot of surface area to absorb more dye and complex dyes based on rubidium to absorb a broad part of the solar spectrum, and achieved efficiency of 7 percent. Subsequently, the efficiency has been improved to over 11 percent. The National Institute for Material Science in Japan holds the record efficiency for a DSSC at 11.4 percent and with an open circuit voltage of 0.743V (NIMS 2011), but most products have efficiency in the range of 4 to 5 percent. These products are used mostly for indoor novelties and art objects, and more development is required before they can be used outdoors where UV light and temperature fluctuations continue to affect the performance.

Organic Cells

The term "organic" refers to carbon-based molecules (plastics, polymers). Different molecules of this type, often including inorganic components such as copper, can be built up in layers using inexpensive materials and processes, and create devices that generate electricity using effects which are different than those of semiconductor devices described above. Plastics are ordinarily insulators, but a p-type semiconductor can be created by doping the plastic with an oxidant such as oxygen or iodine, which transfers an electron from the organic molecule to the oxidant, leaving a hole in the plastic molecule which can conduct charge. An n-type semiconductor can be created by exposure of a polymer to hydrogen, which results in an electron available to conduct charge. A photon of light creates an electron-hole pair; this pair diffuses to a region where the hole and electron are separated; the hole is transferred to the anode and the electron to the cathode to a supply a direct current to our load. Since the mobility of these charges in the plastic material is very low, they must be very thin to conduct current, but they do have very high absorption so they don't need to be thick to capture sunlight. I don't mean to oversimplify the complexity of this approach—the chemistry and electrochemistry is very complicated—but the result is very promising in terms of using common materials and simple processes to construct low-cost PV products. Since they are lightweight and flexible, they could be easily integrated into all kinds of energy-consuming products, tents, and even garments. Organic cells have efficiencies of 1 to 3 percent. Researchers claim that efficiencies of 10 percent are possible (Hoppe and Sariciftci 2004). Reported characteristics of a commercially manufactured organic PV module are listed here (Razykov et al. 2011):

Konarka KT3000: 1.7 percent efficient; –0.0005/C power temperature coefficient

Alan Heeger, who won a Nobel Prize for his work in conductive polymers, founded Konarka in 2001, and although the company has declared bankruptcy, the new owners are interested in continuing the technology pathway. Konarka printed material onto flexible substrates using roll-to-roll manufacturing, similar to the way newspaper is printed on large rolls of paper (Nobel Prize Foundation 2012).

Quantum Dot Cells

Quantum dots are semiconductor crystals with physical dimensions on a nanometer (10^{-9} m) scale, the same scale as many effects described by quantum mechanics. We have established that when the energy of a photon creates an electron-hole pair, photon energy in excess of the band-gap energy is dissipated as heat. However, the excess energy could be used to create another electron-hole pair through "impact ionization," where the excess energy of the first electron contributes to freeing a second electron. When the electron and the hole are confined to dimensions that are on the same order as their wavelength, so that the mechanisms of quantum mechanics are dominant, this impact ionization is just as likely as heat dissipation (Nozik 2001). The effective band gap can be adjusted by the dimensions of the dot, offering a way to use longer-wavelength light not useful to other conversion concepts. Also, since it is the size of the dot rather than the type or structure of the material that is important, inexpensive materials and simple fabrication techniques may be used. Researchers at University of Notre Dame have achieved 5.4 percent efficiency in the laboratory (Santra and Kamat 2012), but commercial products based on quantum dots are not yet on the market. What's exciting about the quantum dots is not their efficiency currrently, but rather it is the rate at which their efficiency is increasing. They went from 2 percent in 2010 to over 5 percent in 1012. Scientists predict that efficiencies as high as 66 percent can be achieved by quantum effects that increase both the current and voltage.

STANDARD RATINGS AND PERFORMANCE INDICATORS FOR PV MODULES

Standard ratings are very important in the PV business because modules are bought and sold based on their *nameplate rating*, P_{rated}, in units of watts, rather than any other unit such as area (m^2, ft^2). The nameplate rating is the maximum power, P_{max}, as measured in a standard test and is printed on the module label along with other parameters such as v_{oc}, i_{sc}, v_{mp}, and i_{mp}. Thus in order to be useful for comparison between products, these parameters must be measured and reported in the same way, or at least we must correct for differences between ratings before making any comparisons.

Interview with PV Researcher Bolko von Roedern

Bolko von Roedern, shown working in the lab in Figure 3-10, earned a physics diploma from Clausthal Technical University, Germany, in 1975 and a Ph.D. in physics from Stuttgart University in 1979 while doing research at the Max Planck Institute for Solid State Research. Dr. von Roedern joined the Solar Energy Research Institute in 1983 following a postdoctoral fellowship at Harvard University. He developed amorphous-silicon-based (a-Si) solar cells at SERI, and in 1985 he helped start solar manufacturers Glasstech Solar, Inc. and MV Systems Inc. In 1992 he returned to SERI as a roject manager responsible for supporting amorphous and crystalline Si, cadmium telluride, and copper indium diselenide thin-film photovoltaic technologies, and he became familiar with organic and wafer-based silicon PV. Scientifically, he pursues an evaluation of how material quality will affect solar cell performance. He has now founded a consultancy, von Roedern & Associates.

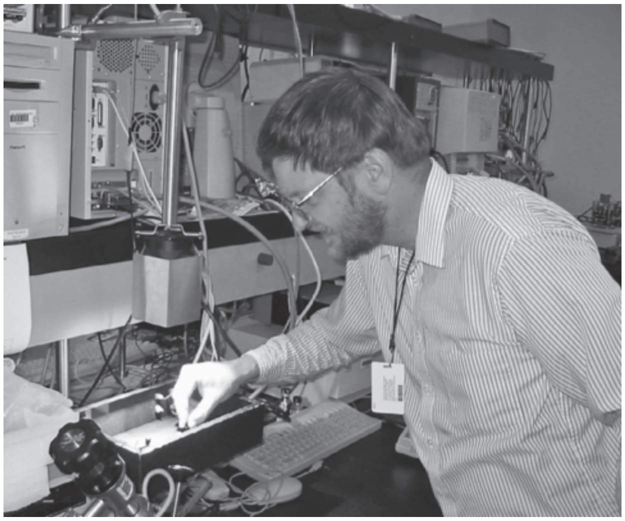


Figure 3-10. Scientist Bolko Von Roedern is an expert on the performance of different types of photovoltaic devices. (Photo courtesy of Bolko Von Roedern)

What are the main thrusts of research into PV devices today?

Historically, champion efficiency, rather than cost, has been the most important objective. But now, a major thrust of PV research is to lower cost. Note that PV is sold in terms of STC (DC kW), while revenues are related to the delivery of energy over the year (AC kWh/year) rather than instantaneous power. Many calculators like PVWatts are used to link rated power to energy delivery.

The variety of PV devices is somewhat overwhelming. Why are there so many approaches to converting sunlight into electricity? Isn't one way best, and shouldn't that be the only way?

There are many approaches, because, in my opinion, nobody has yet answered the question as to what is the "secret' to reaching high performance.

Do you have any advice regarding the different types for someone trying to select or specify a type of PV?

There is not much advantage from cutting performance and price proportionally, so a high efficiency is recommended.

Are there any technology-pathways that you think are the most promising?

Efficiency will ultimately win! Based on what we know today, that is CdTe and CIGS, and perhaps concentrators. Some relative low efficiency approaches (a-Si, nc-Si, Si-film, organic semiconductors, nanostructures) should continue to be researched, but can be commercialized only after 15 percent stabilized cell efficiencies are demonstrated. I stress the fact that about half the cost of a crystalline-Si PV module is the crystal wafer, which may be saved with a thin-film approach. I have not worked enough with concentrators to have gained insight about their cost-effectiveness.

Tell us what you think PV products and PV research will be like 10 or 20 years from now.

Things are changing very rapidly, but there could still be a mix of different technologies used in 10 to 20 years. One cannot show experimentally that any approach has reached the end of the line [further efficiency and cost improvements are not possible]. There is also some chance that something new will be discovered. R&D will continue to deal with materials used today, as it has taken much longer than thought to conduct required R&D on these materials. If there is a breakthrough, there will be subsequent R&D on that, too, which will take a long time. I advocate believing in experimental observations, not theoretical expectations, but I don't know if such an opinion will prevail. There will be significantly more work on performance and reliability, in addition to cost and efficiency, in the future.

International Electrotechnical Commission (IEC) issues standard IEC 61853-1 which requires that module performance be reported under 5 different sets of conditions:

1. Standard Test Conditions (STC)
   These conditions depend on the application (in space, on earth, focusing, non-focusing). For nonfocusing modules for use on earth, the specified STC insolation is $I_c = 1000$ W/m^2 and the cell temperature is $T_{cell} = 25$C (78°F). Notice that this is the temperature of the cell itself, which may be 20C or so warmer than the surrounding air. For focusing collectors, the standard for insolation of direct beam radiation is 850 W/m^2 (IEC 2006). The associated ASTM standard uses the term "Standard Reporting Conditions" (SRC) to acknowledge that measurements may be made under different conditions, corrected to a value corresponding to STC, and then reported (ASTM 2008). ASTM standard G173-03 specifies the details of the spectral distribution (wavelengths) of the insolation to

be applied during the test. To account for the thickness of the atmosphere as light comes through it at an angle, this spectrum is known as *1.5 air mass* (1.5 AM), which is 50 percent more air between your panel and the sun than if the sun were directly overhead, to account for sunlight passing through the atmosphere at an angle. This standard atmosphere is used in all five test conditions.

2. Nominal Operating Cell Temperature (NOCT)
   Insolation $I_c = 800$ W/m^2; ambient temperature $T_{ambient} =$ 20C; wind speed = 1 m/s to specify air movement cooling the module. Cell temperature is then measured and reported along with power output.
3. Low Irradiance Conditions (LIC)
   Insolation $I_c = 200$ W/m^2; module temperature $T_{cell} = 25$C
4. High Temperature Conditions (HTC)
   Insolation $I_c = 1000$ W/m^2; module temperature $T_{cell} = 75$C
5. Low Temperature Conditions (LTC)
   Insolation $I_c = 500$ W/m^2; module temperature $T_{cell} = 15$C

STC conditions are very rare in practice. Insolation is often less than 1,000 W/m^2 and cell temperature is often greater than 25°C. On a hot summer day the cell temperature may easily exceed 50°C (120°F). In an attempt to represent ratings under more realistic conditions, the organization PV for Utility Scale Applications (PV-USA) specifies "PV-USA test conditions" (PTC) as 1,000 W/m^2 plane-of-array irradiance, 20C ambient temperature, and 1 m/s wind speed. A nameplate rating based on PTC is about 12 percent lower than one based on STC (NREL 2011). Manufacturers do not typically publish PTC values, but since they have been adopted by use by the California Energy Commission for use in administering incentive programs, they may be found on the CEC website at www.gosolarcalifornia.org/equipment/pv_modules.php.

Given the A_C, P_{max}, and I_C associated with the testing, an efficiency, η, may also be calculated and reported. Both STC and PTC rating criteria tend to overestimate how much energy a PV module will generate under real-world conditions, so we refer to whole-systems models using weather data for a site to generate credible energy delivery estimates—but all of these models use the results of these standards rating tests as input to the models and adjust them for actual conditions.

Nameplate Rating and Datasheets for PV Modules

The nameplate of a PV module, a label affixed to the back of a module, provides most but not all of the information required to evaluate a module and design a system. The label typically contains:

- The manufacturer of the PV module
- Model number
- Serial number
- P_{max}: rated power at maximum power point (W), under STC conditions
- v_{oc}: open circuit voltage (V), under STC conditions
- v_{mp}: voltage at maximum power point, under STC conditions
- i_{sc}: short circuit current, under STC conditions
- i_{mp}: current at maximum power point, under STC conditions

Symbols representing the various standards that the module may satisfy including American Society of Testing and Materials (ASTM); Institute of Electrical and Electronics Engineers (IEEE);, and International Electrotechnical Commission (IEC). The TUV symbol is an indication that the module satisfies IEC standards. The CE symbol represents that the module satisfies European Union regulations, and the UL marking indicates compliance with UL standards. For more on standards, see the section of this chapter on Codes and Standards below.

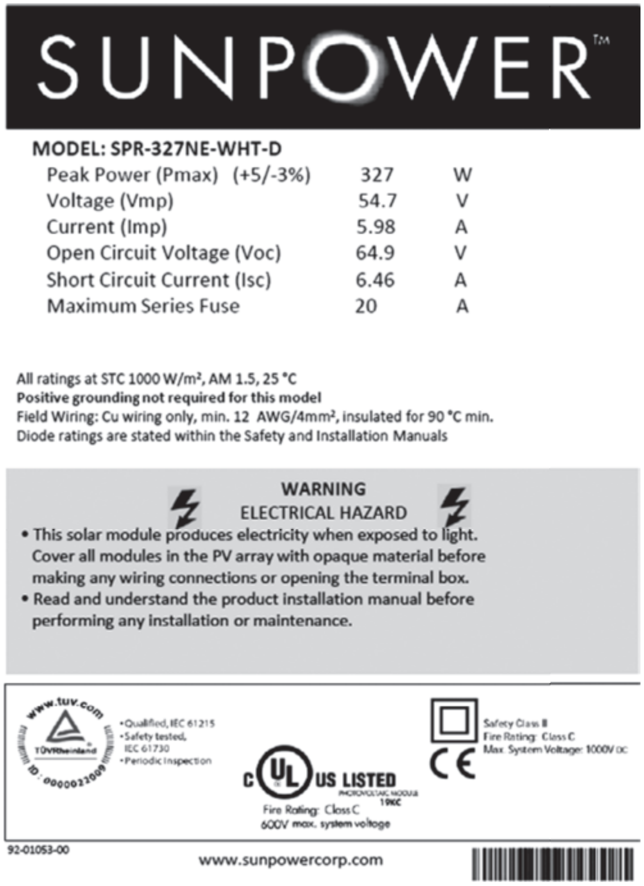
An organization called "Solar America Board for Codes and Standards" (Solar ABCS) has issued "A Proposed Standard for: Nameplate, Datasheet, and Sampling Requirements of Photovoltaic Modules" (TamizhMani, Kuitche, and Mikonowicz 2012), which recommends including the above listed information on the nameplateas well as:

- The maximum system voltage that the module may be subjected to (often 600 V_{dc} in the USA, 1000 V_{dc} in Europe).
- Maximum production tolerance (+/–%) on P_{mp}

On the datasheet advertised and included in the shipping box for each module, the Solar ABCS recommendations include all of the above information plus temperature coefficients (1/C or %/C) for v_{oc}, i_{sc}, and P_{mp}. These are very important pieces of information for the designer, since the v_{oc} under the coldest conditions at a site and i_{sc} under the sunniest conditions must be used to configure the modules in an array and size the conductors from the array. Thus these coefficients must be used in a calculation that is specific for each site and associated climate extremes.

The Solar ABCS recommends including the result of all five of the IEC 61853-1 tests (STC, NOCT, LIC, HTC, and LTC) on the datasheet for a module, but since Solar ABCS is not a standards-making organization, these standards are not compulsory and this additional information may or may not be in the manufacturers literature for a given PV module. The Solar ABCS recommendations also include increasing the percentage of modules from a production line that are actually tested and the allowable tolerance (variation) from the published numbers. The recommendations require that the average power measured of all the modules in a sample be greater than the rated power and that no single module be less than 3 percent of rated power.

In Europe, nameplates and datasheets are required to abide by standard EN 50380: "Datasheet and Nameplate Information for Photovoltaic Modules," issued in 2003. This standard requires reporting of P_{max}, v_{oc}, v_{mp}, i_{sc}, i_{mp} at STC; at nominal operating cell temperature (NOCT); and under low-irradiance conditions (LIC). It also requires publication of temperature coefficients (%/C) on voltage and current. The European standard allows uncertainty in the measurement and in the production



SUNPOWER™

MODEL: SPR-327NE-WHT-D

Peak Power (Pmax) (+5/-3%)	327	W
Voltage (Vmp)	54.7	V
Current (Imp)	5.98	A
Open Circuit Voltage (Voc)	64.9	V
Short Circuit Current (Isc)	6.46	A
Maximum Series Fuse	20	A

All ratings at STC 1000 W/m², AM 1.5, 25 °C
Positive grounding not required for this model
Field Wiring: Cu wiring only, min. 12 AWG/4mm², insulated for 90 °C min.
Diode ratings are stated within the Safety and Installation Manuals

WARNING
ELECTRICAL HAZARD

- **This solar module produces electricity when exposed to light. Cover all modules in the PV array with opaque material before making any wiring connections or opening the terminal box.**
- **Read and understand the product installation manual before performing any installation or maintenance.**

www.tuv.com
TÜVRheinland
ID: 0000022009
•Qualified, IEC 61215
•Safety tested, IEC 61730
•Periodic Inspection

c UL US LISTED
PHOTOVOLTAIC MODULE
19KC
Fire Rating: Class C
600V max. system voltage

Safety Class II
Fire Rating: Class C
Max. System Voltage: 1000V DC

92-01053-00

www.sunpowercorp.com

Figure 3-11. The "nameplate" label of a PV module lists performance characteristics such as rated power, open circuit voltage, and closed circuit current, as well as the warning labels and certifications that the module has earned. (Courtesy of SunPower Corp.)

tolerance to add. For example, if a measurement was +/–3 percent and the stated production tolerance was +/–4 percent, then a given module may be 7 percent less than stated on the nameplate and still be within specification. Figure 3-11 is an example of an actual PV module nameplate.

ENERGY BALANCE FOR A PV MODULE, NOMINAL OPERATING CELL TEMPERATURE (NOCT)

Consider a PV module with a frontal area A_c (m^2). The solar radiation incident on the collector, I_c (W/m^2), as measured in the plane of the array, is calculated as the sum of direct beam, diffuse, and ground reflected radiation as described in Chapter 2 of this book describing the solar resource. Some of this will be reflected off the cover glass or absorbed in dirt on top of the cover glass. The fraction that is not is τ, the transmissivity of the glass or plastic cover. Again, some will be reflected back out of the module off of the PV cell, and the fraction that is not is α, the absorptivity of the PV cells. The first law of hermodynamics tells us that energy is not created or destroyed within the PV module, and the absorbed solar radiation that is not exported from the module as electricity is manifested as heat, thus increasing the temperature of the module above that of the ambient temperature. The heat loss per unit temperature increase above ambient is U_l, the heat loss coefficient (W/m^{2}C or Btu/hrFft^2). The energy balance for a PV module is thus:

$$K\tau\alpha I_c A_c - iv - U_l A_c(T_{\text{cell}} - T_{\text{ambient}}) = 0 \tag{3-20}$$

Where i is the current out of the module in amps and v is the voltage that the current is maintained at in volts. K is the *incident angle modifier*, which is defined as the ratio of $\tau\alpha$ measured at the angle of incidence of the incoming light to the value of $\tau\alpha$ measured normal to the glass. Calculation of the incident angle, $\ominus$, as a function of time-of-day and day-of-year is described in the solar resource section of this book, and

$$K = 1 + b\left(\frac{1}{\cos\theta} - 1\right) + c\left(\frac{1}{\cos\theta} - 1\right)^2 \tag{3-21}$$

Where b and c are curve-fit parameters determined by the testing procedure. Use equation 3-21 only for $\ominus < 60$ degrees, and use a linear relationship between the K calculated at 60 degrees and $K = 0$ at $\ominus = 90$ degrees for higher incident angles. Remember that K and Equation 3-21 do not include the cosine effect of the incoming solar radiation being spread over the collector area, that is taken care of in the calculation of I_c. Although it is possible to consider all three sources of radiation separately (direct beam, diffuse, ground reflection) and apply an incident angle modifier only to the direct beam component, for simplicity here we apply the incident angle modifier to I_c, the sum of all three.

The measured parameter called nominal operating cell temperature, NOCT, (C or F) is the T_{cell} measured under conditions of insolation $I_c = 800$ W/m^2; ambient temperature $T_{\text{ambient}} = 20$C; and normal incidence K = 1. Both the front and back of the module are exposed to an imposed 1 m/s wind speed. The NOCT as measured in the test may be printed on the module nameplate or published in the manufacturer's literature and is often on the order of 45°C or 48°C. Recognizing that $P_{\max} = iv = \eta I_c A_c$, and substituting NOCT into the energy balance, Equation 3-20 gives us a chance to lump all the other physical characteristics of the PV module together and solve for:

$$\frac{(K\tau\alpha - \eta)}{Ul} = \frac{(\text{NOCT} - 20\text{C})}{\left(800\dfrac{W}{m^2}\right)} \tag{3-22}$$

Solving the energy balance Equation 3-20 for the cell temperature T_{cell} gives:

$$T_{\text{cell}} = T_{\text{ambient}} + \frac{(K\tau\alpha - \eta)}{Ul} I_c \tag{3-23}$$

Or upon substituting Equation 3-22 into Equation 3-23

$$T_{\text{cell}} = T_{\text{ambient}} + \frac{(\text{NOCT} - 20C)}{\left(800\dfrac{W}{m^2}\right)} I_c \tag{3-24}$$

Strictly speaking, the voltage v_{mp} is also a function of temperature, so as T_{cell} gets hotter, the voltage goes down and less power is removed electrically from the cell, and the cell gets hotter still. The Equation 3-21 does not take this additional heat into account. We could iterate until we found the T_{cell} that balances the energy equation with voltage as a function of temperature, but since the voltage of each cell only varies a few tenths of a percent per degree C, this nonlinear effect is neglected.

Note that the standard test for measuring NOCT allows air to circulate on both the front and back of the module. If the module is mounted flat on a roof so that air may not circulate behind it, then the operating temperature may be 10°C (20°F) or more hotter than T_{cell} calculated by Equation 3-24. A simple approximation of this condition is to say that the product of heat loss coefficient U_l, and area A_c, is reduced by half, so that the cell temperature of a module mounted flat on the roof is approximately

$$T_{\text{cell,flat on roof}} = T_{\text{ambient}} + \frac{2^{*}(\text{NOCT} - 20C)}{\left(800\dfrac{W}{m^2}\right)} I_C \tag{3-25}$$

POWER OUTPUT OF A PV MODULE

Finally, we have described each of the terms needed to calculate the power output of a PV panel under given ambient conditions of insolation and temperature. Calculation of the current and voltage from the i-v curve results in the power output at any imposed voltage. But even in simple systems voltage is adjusted to deliver nearly the maximum power. Thus, we restrict our attention to the calculation of P_{mp} as a function of temperature and insolation.

$$P_{\text{solar}} = \frac{P_{\text{STC}} K I_c}{(I_{\text{STC}})}[1 - \delta(T_{\text{cell}} - T_{\text{cell, STC}})] \tag{3-26}$$

Where standard test conditions are $I_{\text{STC}} = 1{,}000$ W/m^2; and $T_{\text{cell,STC}} = 25$C. Using the efficiency, $\eta = P/I_c A_c$, measured under STC conditions, we can also express power output as

$$P_{\text{solar}} = A_c K I_c \eta_{\text{STC}}[1 - \delta(T_{\text{cell}} - T_{\text{cell,STC}})] \tag{3-27}$$

Where η_{STC} is the efficiency of the PV modules under standard test conditions. For cell temperatures other than STC conditions, we can calculate efficiency as

$$\eta_{\text{solar}} = \eta_{\text{STC}}[1 - \delta(T_{\text{cell}} - T_{\text{cell,STC}})] \tag{3-28}$$

Equation 3-27 provides a way of calculating the power output of the PV module as a function of the performance of the module measured under standard test conditions (STC), which are commonly reported in the manufacturer's literature, and the extant environmental conditions I_c and T_{ambient}. The cell temperature T_{cell} is also a function of these environmental conditions I_c and T_{ambient}.

Substituting the relation of Equation 3-24, the expression for Tcell as a function of NOCT, into Equation 3-27, the power output of the solar system may be calculated as

$$P_{\text{solar}} = P_{\text{STC}}\left\{\frac{(\eta_{\text{bos}} * \text{deg}r)}{\left(\dfrac{1000W}{m^2}\right)} I_c \left(1 - \delta\left(\left(T_{\text{ambient}} + \frac{(\text{NOCT} - 20C)}{\left(\dfrac{800W}{m^2}\right)} I_C\right) - 25C\right)\right)\right\} \tag{3-29}$$

Where P_{solar} = power output of the solar system in kW; P_{STC} = rated size or nameplate capacity in kW; η_{BOS} = balance of system efficiency = 0.77 (NREL 2011); degr = an age degradation factor that is 1.0 initially but degrades at a rate of approximately 0.5 percent per year. For an average over a 25-year period, a degradation factor of degr = 0.94 provides an estimate of the degradation levelized over the years. I_c = solar in plane of array (W/m^2). The factor δ = temperature coefficient of power (1/C), which is usually on the order of 0.004 1/C. T_{ambient} = ambient temperature (C); NOCT = nominal operating cell temperature, which is a number found in the manufacturer's literature and is often around 47°C. Conversely, if we know P_{solar} as the amount of power that we need to get from a system, we can use Equation 3-29 to calculate how many watts rated at STC would provide that amount of power.

Example Calculation of the Power Output of a PV Module based on Rating Data

In this example we calculate the instantaneous power output of a PV module under specified ambient conditions (sunlight and temperature) using the results of the standard rating test as reported in the PV manufacturer's literature.

The PV module under consideration is rated at 230 watts under Standard Test Conditions (STC). Other specifications of the PV module are listed in Table 3-4. The incident angle modifier is reported by the test data as $K = 1 - 0.078{*}(1/\cos(\ominus) - 1) - 0.086{*}(1/\cos(\ominus) - 1)^2$. The ambient conditions are: 800 W/m^2 (254 Btu/ft^2/hr) solar incident on the module; and 27 C (81 F) ambient temperature. We are asked to calculate the power output of the module under these conditions and the efficiency. We proceed through the equations from earlier in this chapter, and the results from each equation are listed in Table 3-4 in the order that they are calculated.

We find that under these conditions, the PV module would deliver 138 W, significantly less than its nameplate STC rating of 230 W, even under these rather sunny conditions. The efficiency is calculated at 16.6 percent in this example.

TABLE 3-4. EXAMPLE OF CALCULATED POWER OUTPUT OF A PV MODULE UNDER SPECIFIED AMBIENT CONDITIONS

PV Module Specifications	Description	Value	SI Units		IP Units
P_{STC}	Power of module at standard test conditions	230	Watts	+/–5%	
P_{PTC}	Power of module at performance test conditions	213.5	Watts		
v_{mp}	Voltage at max power	41	V		
i_{mp}	Current at max power	5.61	A		
v_{oc}	Open-circuit voltage	48.7	V		
i_{oc}	Short-circuit current	5.99	A		
δ	Power temperature coefficient	–0.0038	1/C		
α	Current temperature coefficient	0.000584	1/C		
β	Voltage temperature coefficient	–0.00271	1/C		
NOCT	Nominal operating cell temperature	45	C	113.2	F
η_{STC}	Efficiency at standard test conditions	0.185			
Length		1.559	M	5.11	Ft
Width		0.798	M	2.62	Ft
Weight		15	Kg	33.00	Lbs
Ambient conditions					
I_C	Solar radiation	800	W/m^2	253.7	Btu/hft^2
$T_{ambient}$	ambient temperature	27	C	80.8	F
Calculations					
A_c	Area	1.24	m^2	$13.38	ft^2
K	incident angle modifier Equation 3-21	0.836			
Energy balance					
T_{cell}	PV cell temperature (Equation 3-24)	52	C	125.8	F
η_{solar}	Efficiency at T_{cell} (Equation 3-27)	0.166			
P_{solar}	Solar power delivery (Equation 3-29)	138.13	W		

PHOTOVOLTAIC SYSTEM SCHEMATIC DESIGN

Schematic design of a PV system specifies the size, type, and location of major components. The components of a system depend on what the system needs to do, with systems that require more functions requiring more components to perform those functions. The schematic phase of design should list out the following details regarding components:

- PV modules: number of modules, series and parallel wiring configuration of PV array; manufacturer and model of PV modules with key performance parameters such as:
  - Rated power (W)
  - Collector dimensions: length, width (m,ft), area, (m^2, ft^2);
  - Open circuit voltage (volts)
  - Short circuit current (amps)
  - Voltage temperature coefficient (1/C)
- Location and type of rack and foundation or attachments to structure.
- Combiner boxes: number of combiner boxes, number of source circuits into combiner box; rating of fuse (amps) on each source circuit into combiner box.
- Overcurrent protection: rating (amps) of fuse or circuit breaker
- Charge controller: the schematic design describes central or local controls and charge sequence; temperature compensation.
- Batteries: size (Ah or kWh) and type; environmental requirements; charge sequence
- Inverter: size (kW); DC voltage window (minimum and maximum voltage from the array under which the inverter will operate); AC voltage and configuration of phases (single phase 120; single phase 240; three phase 480) compatible with the building electrical system.

One key consideration is that the number of PV modules in series must produce a voltage that matches the operating voltage of the maximum power point tracker of the inverter or charge controller. This affects not only the design of how many modules may be wired in series but also the selection of modules and inverter themselves. Lists of possible module configurations are published by inverter suppliers.

Direct Drive PV System

There are many applications where a PV system can power a load directly without batteries or without a connection to the utility system. For example, a PV cell used to power a calculator would work, assuming that you don't do your accounting in the dark. Often it is much easier to store the desired product (pumped water, chilled water, ice, heated water) than it is to store electric charge. A fan to ventilate a composting toilet or to dry crops would be similar—the fan would run only when the sun is shining, but that is sufficient.

Components of the direct drive PV system consist only of the PV array and the device to be powered, although other controls and maximum power point tracker to couple the optimal voltage of the array to the load would be typically included.

Figure 3-12 shows a diagram of the major components of a PV system to power water pumping for watering livestock or crops. This is a good example of a direct-drive type of PV system because the solar can pump water when the sun is shining and then the water is stored in a tank for when the livestock are thirsty. I received a Solar Achievement Award from the Interstate Solar Coordinating Council in 1993 for teaching ranchers how to install these types of systems.

Direct-Current (DC) Off-Grid PV System with Battery Storage

To provide electric energy when the sun is not shining requires battery storage. Batteries then require charge controller and low voltage disconnect. Such a system can power any DC load for any period of time—but cost-effectiveness usually requires that not all loads will be powered simultaneously, and there will be periods of time when the load is disconnected because the batteries are discharged and there is no sun. Due to a market in boats and recreational vehicles, there is a very wide variety of appliances from lights to air conditioners and refrigerators, to kitchen appliances and consumer electronics that are available for use with DC power supplies.

Components of DC off-grid PV systems with battery storage include: PV array; array DC disconnect; charge controller; battery DC disconnect; low-voltage disconnect; and battery. The schematic diagram of Figure 3-13 shows how these major components are arranged in a system.

Alternating Current (AC) Off-Grid System with Battery Storage

In the late 1800s, Westinghouse and Edison fought over whether our electric system should be alternating current or direct current (AC or DC)—Westinghouse won. So most of our appliances are manufactured to operate on AC power. AC has the advantage of being easily transformed to different voltages by a "transformer" which converts the electric field to a magnetic field and then back to an electric field of any voltage. Alternating current can also be configured in multiple phases (3-phase systems). A DC arc continues, whereas an AC arc extinguishes itself 50 or 60 times per second—allowing less expensive breakers and switching equipment for AC circuits. Since the PV modules generate DC current

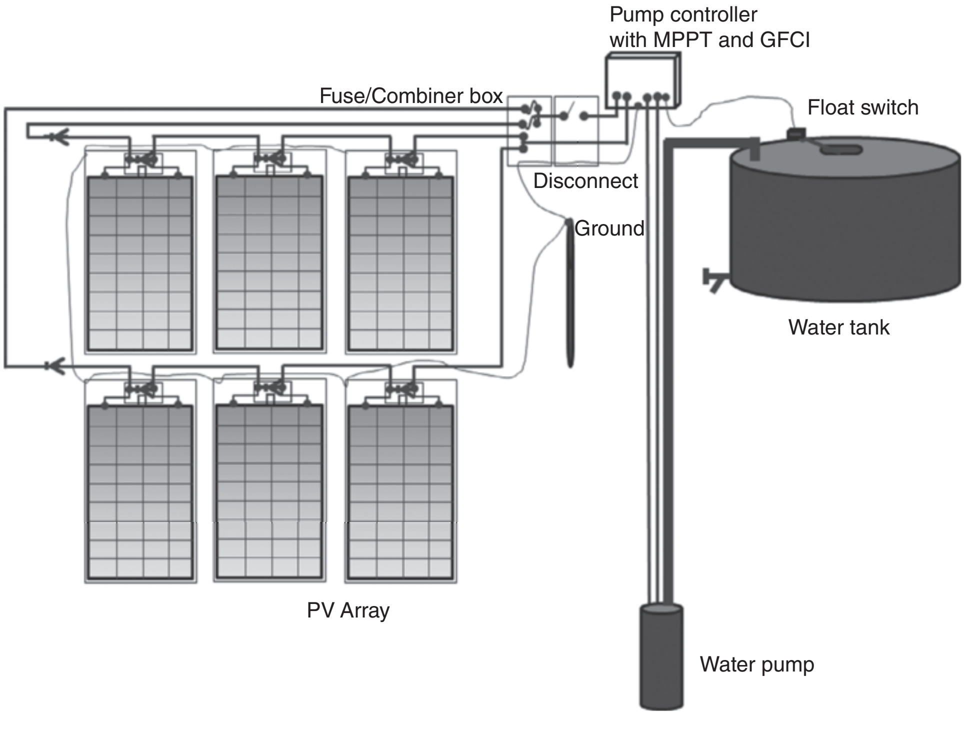


Figure 3-12. Schematic diagram of a direct-drive PV system with no batteries or inverter. This example is a water pump for livestock. (Figure by the author)

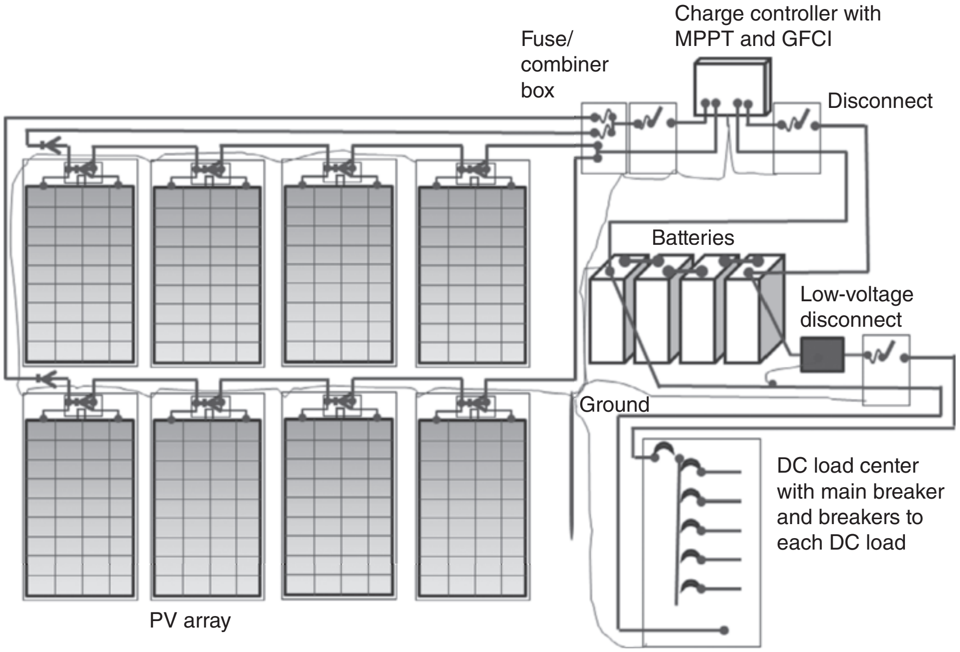


Figure 3-13. Schematic diagram of DC off-grid PV system with battery storage and Charge controller. (Figure by the author)

and the batteries store DC, an inverter is required to generate AC power from the DC source. Since there is no grid to synchronize with, the off-grid inverter generates its own signal of the desired frequency according to a timing device within the inverter.

Components of an AC off-grid PV system with battery storage include: PV array; array DC disconnect; charge controller; battery DC disconnect; battery; low voltage disconnect; inverter; and AC disconnect. Figure 3-14 shows how these components may be arranged in an off-grid PV system with battery storage.

Hybrid PV/Generator System

Combining a PV array with a conventional diesel- or propane-fueled generator is a good combination for off-grid loads where

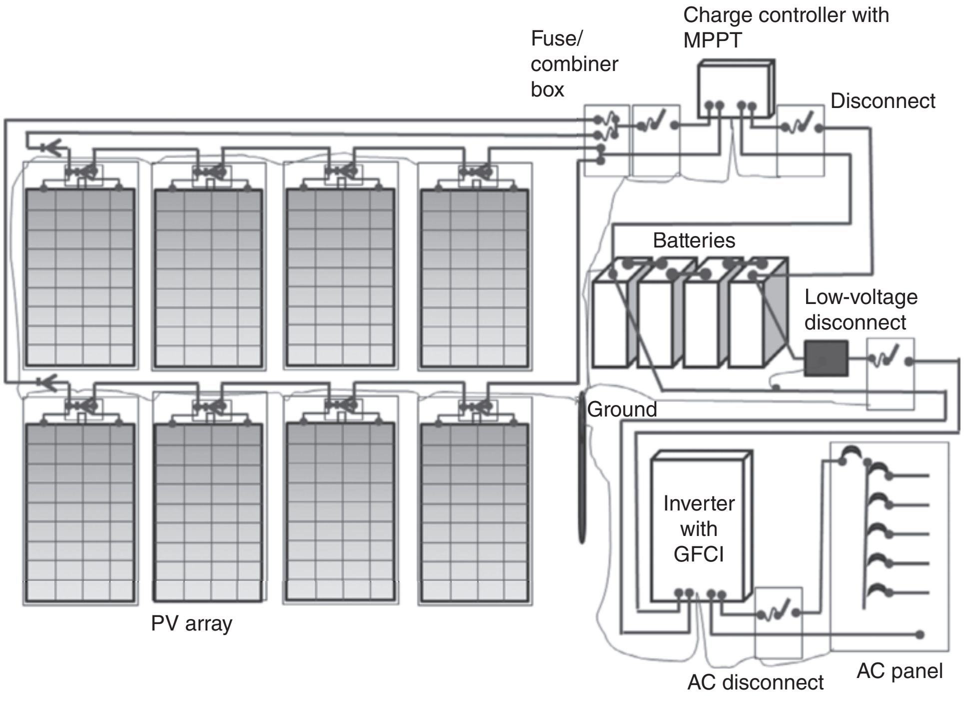


Figure 3-14. Schematic diagram of alternating current (AC) PV system with batteries and inverter. (Figure by the author)

the utility is not available. The PV array can be sized to provide most of the energy, but the generator provides reliability. The advantage of the PV is a low operating cost and the disadvantage is a high initial cost. The advantages of the generator are that it is inexpensive and provides power whenever needed, and the disadvantage is that fuel costs money. But if the generator is turned off because the load is served by solar, we get the reliability of the generator without the expense.

The optimal combination of PV and generator use depends on the cost of fuel and maintenance for the generator, the solar resource at the site, and the cost of the PV system. Generally it is cost-effective to meet about two-thirds or three-quarters of the energy requirements with solar. But this reduces the generator run time much more than that fraction. When the generator is on, it runs at full capacity—delivering the same kWh in a shorter run-time.

The control sequence for a hybrid PV/generator system is as follows: When the battery bank reaches a set-point minimum voltage, perhaps adjusted for temperature and current out of the battery, an automatic generator starter cranks the engine/generator. When the generator comes up to full voltage, a transfer switch transfers the load from the inverter to the generator. A battery charger is also powered by the generator. When the batteries are back to their set state of charge voltage, the generator will automatically turn off and the transfer switch will transfer back to serving the load from the inverter. Such as system to cyclically charge batteries rather than running a generator at a small fraction of its power capability is cost-effective even without the photovoltaics.

Components of a hybrid PV/generator system include: PV array; any number of combiner boxes; array DC disconnect; charge controller; battery DC disconnect; low voltage disconnect; inverter; AC disconnect; automatic generator starter; and generator.

Utility-Connected, Grid-Tied PV System

If a utility system is available to serve the loads at night or cloudy periods, then batteries are not needed. If utility policy allows power to flow both ways and the utility has a net-metering policy, then the utility is just like a 100 percent efficient, free, battery to store electricity for when it is needed. Also in a grid-tied system there is no need to meet all of the load with solar—many PV systems have been installed that only meet a few percent of the building load. The voltage of grid-tied systems is also higher than typical battery voltages allowing for lighter wires and hardware and more efficient, less expensive systems. The off-grid market has been developing since the 1980s, but in 2005 grid-tied systems began to become more common, and now grid-tied systems represent entirely the growth in the PV industry. Without batteries, the grid-tied PV system is an entirely solid-state electronics power supply system with very little planned maintenance compared to other types of electric generators.

Components of a grid-tied PV system include: PV array; any number of combiner boxes; DC disconnect; inverter; AC disconnect; transformer; and utility connection. Figure 3-15 shows how these major components are arranged in a grid-tied PV system.

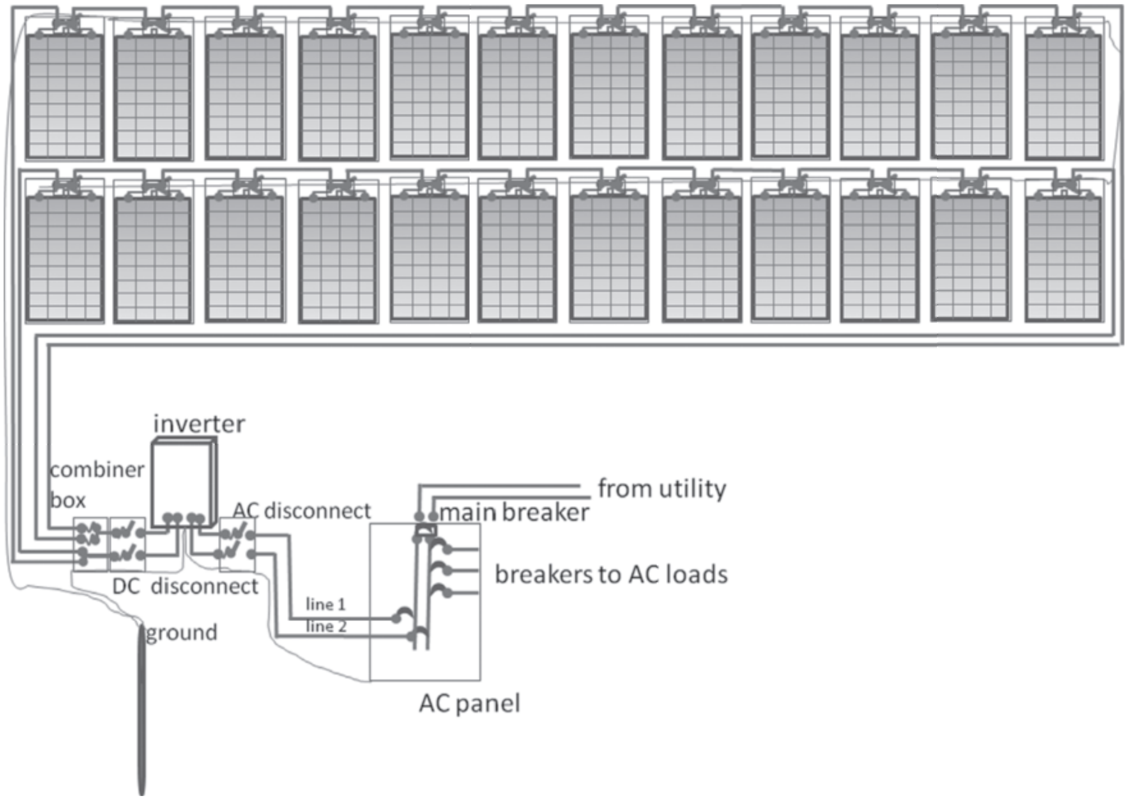


Figure 3-15. Schematic diagram of grid-tied PV system with inverter. (Figure by the author)

Building-Integrated PV System

This system type is distinguished only by the fact that the PV array is integrated into some aspect of the building envelope. There are many examples including:

- Flexible thin film PV adhered to single-ply membrane roofing
- Flexible thin-film PV adhered to the pan of standing seam metal roofing
- Flexible thin-film PV shaped to match composite roofing shingles
- PV integrated into opaque spandrel glass
- PV integrated into partial-transmissivity window glass
- PV as a shade over windows

Many PV modules are fabricated as strong laminated glass assemblies, and thus are easy to install in building systems such as curtain walls that involve glass. The challenge is how to connect the systems electrically while still observing all code requirements for wire installation. If the wires are installed in conduit right from the PV module terminal boxes, it seems all codes would be satisfied. But if the window mullion system itself is used to route conductors, the whole system would have to be UL listed. It turns out that the PV cells themselves are the expensive part, and it is not that expensive to have custom-dimensions fabricated. However, the requirement that the building-integrated system as a whole meet all codes limits creativity. Requirements include not only electrical safety but also those related to the physical strength of the glass and safety of such glass overhead or in other building applications (hurricane, seismic, etc.). For example, the atrium at the Thoreau Center for Sustainability in San Francisco has 1.2 kW of PV overhead, with 17% open spacing between cells to admit daylight—but a layer of safety glass had to be installed underneath the PV because the PV glass had not been certified to meet all requirements of overhead glass in San Francisco.

PHOTOVOLTAIC SYSTEM COMPONENTS

Here we consider some of the details of components that make up a photovoltaic power system. Not all of these components will be used in every system—the components depend on what the system is being designed to do (off-grid DC, off-grid AC, grid-tied AC.

Photovoltaic Modules

Photovoltaic cells are wired in series and parallel to provide the desired voltage and resulting current (power) in "modules." Modules usually have a tempered glass cover and a backsheet of glass or a plastic called tedlar with the cells encapsulated in an ethyl vinyl acetate (EVA) glue, thus forming a very strong laminate. Modules usually have an aluminum frame but may also not have a frame. Each module is sized for ease of handling and mounting, but a trend toward larger modules is an attempt to reduce installation cost in utility-scale systems—a crane might even be required to handle "large-format" modules. The frame usually provides the mounting holes so if there is no frame, mounting fixtures are glued to the back side of the module. Two or more ribbon-shaped conductors leave the laminate into a junction box on the back of the module. This junction box may also have diodes according to the module design, and terminals for making connections to an external circuit. Water-tight seals are very important to keep water and bugs from getting into the junction box and strain-relief on the incoming conductors is needed to keep electrical connections from pulling loose.

The number of cells in series determines the voltage of the module. For off-grid systems, 36 cells in series would typically provide the 17 or so volts required to charge a 12-volt battery. Modules are also available to charge 24-volt battery systems. For grid connected systems, module voltages are typically closer to 50 volts.

Often a manufacturer's catalog will list several models with nearly the same rated power: say 200, 205 and 210 watts. This is because there are variations that can affect efficiency in the manufacturing process, so each module is tested as it comes off the manufacturing line, and they are sorted according to the measured power and stated tolerance. For example, a module that tests at 204 watts would be labeled as "210 W +/– 3 percent." And one that measured 194 watts would be labeled "200 W +/ – 3 percent." Suppliers might sell with a zero tolerance, meaning that they are labeled such that each one delivers its rated power.

The average price per watt for a single PV module is reported at \$2.29/W_{STC} in 2012, but as low as \$1.10 for single-crystal silicon; \$1.06/W_{STC} for multicrystal silicon; and as low as \$0.84/W_{STC} for a thin-film PV module (Solarbuzz 2012)

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TIP

Selecting a PV Module for your System

There are several important considerations when choosing a PV module:

1. Voltage: For off-grid systems, the voltage under actual operating conditions must be sufficient to charge the battery or power the off-grid device directly. For grid-tied systems, the voltage of modules in series must provide the minimum but not exceed the maximum voltage rating of the system (often 600 V_{DC} in the US, 1000 V_{DC} in Europe), even at record-low temperatures.
2. Actual conditions versus STC conditions: STC conditions are unrealistic (insolation high; temperature low), so look at module performance under the conditions you expect. For example, one module is rated for 224 W under STC conditions and 193 W under more realistic PTC conditions, whereas another one is rated for 215 W under STC conditions but 200 W under PTC conditions. The second module

would be better choice for most applications, despite its higher STC rating.

3. Efficiency: High-efficiency modules (such as singe crystal silicon or silicon heterostructures) may be more expensive than less efficient modules (thin films), but they may produce more than 160 W/m^2 (16 W/ft^2), whereas the less efficient module may produce only 100 or 120 W/m^2 (10 or 11 W/ft^2), or less. In order to compare the cost of these two alternatives, we would have to include the cost of rack, foundation, conductor, conduit, and installation labor in order to do a fair comparison. Often it is worth it to pay a premium for high module efficiency in order to get a smaller system with a lower system cost. Area available to mount modules on a roof may also be limited, requiring the more efficient module to get the desired amount of power.
4. Temperature coefficients: Generally, modules that are insensitive to temperature (small magnitude of temperature coefficients) are preferred because the modules usually operate at a temperature elevated well above the STC or even the PTC conditions. Performance should be compared at the temperature at which the modules are expected to operate, which depends on climate.
5. Manufacturing tolerance: Manufacturers should state their manufacturing tolerance on the nameplate or datasheet for a module. Although the tolerance is stated "plus or minus," it is always "minus." For example, a module rated 200 W +/–3 percent could be as low as 194 W. If it were indeed 200 W, it would be labeled 205 W +/–3 percent. Take this into account when selecting modules or calculating how many modules you need.

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Photovoltaic Arrays

Some small systems may utilize a single PV cell or module, but in general modules are wired together into series and parallel arrangements called "arrays."

MODULES IN SERIES STRINGS (VOLTAGE ADDS)

Modules are wired in "series" by connecting the positive (+) terminal of one module to the negative (–) terminal of an adjacent module in such a way that the voltages add. This is called a "series string" or a "source circuit." Wiring modules in series is generally desirable since $P = i*v$, and a higher voltage results in less current for the same amount of power. Since losses in wiring equal i^2*R, where R is the resistance of the wire, high voltage and low current results in the ability to purchase smaller diameter wires (which are much less expensive due to the cost of copper), and experience less wire losses. High voltages also couple better with the high-voltage architecture of grid-tied inverters, enhancing overall system efficiency.

Each series string includes a fuse to protect wiring from excessive current.

STRINGS OF MODULES IN PARALLEL (CURRENT ADDS)

Series strings of modules are wired in "parallel" by connecting the positive (+) terminal of one module or string with the positive (+) terminal of another, and similarly connecting the negative (–) terminals together. This connection is made in a "combiner box" where all the series strings are combined into larger conductors.

As noted above, each series string requires a fuse. These fuses are located in the combiner box and are usually on the positive side but may be on the negative side if the array has a "bi-polar" wiring configuration. Parallel connection of modules or strings without a fuse in each string is generally prohibited by code requirements. Figure 3-16 is a diagram showing both series and parallel connections between PV modules.

SERIES AND PARALLEL CONSIDERATIONS

Modules are wired in "series strings" to provide the desired voltage, and then series strings are wired together in parallel to provide the desired current and overall power. Wiring modules in series has the advantage of lower current and lower wire losses. However, there are limits to the benefits of series wiring and instances where parallel wiring is preferred.

Most products such as wire, breakers and PV modules themselves are rated for voltages up to 600 V DC (UL-listed) or 1000 V DC (IEC). This limit is imposed by the integrity of the electrical insulation. So the number of modules that we may wire in series is limited by this value and the voltage of each module at the coldest expected temperature. For example, say we are considering modules that are 50V apiece at 25C but 60V at the –20C minimum temperature expected at a site: we could wire a maximum of 10 of these in series and still obey the 600V limit.

Another disadvantage of series arrangement is that the current through the series string is limited by the current through the module with minimum current. This "mismatch" loss is always responsible for a few percent loss in a series string, but is much worse if a module is shaded or damaged. The use of "bypass diodes" around each module in series provides an alternative path for current, prevents electrical damage to the shaded module, and can maintain some, albeit reduced, power delivery from the unshaded modules in the string even if a module is shaded. Ordinarily, the bypass diode blocks current, but when the module is shaded it become "forward biased" and allows current to flow on to the next module. PV manufacturers often provide bypass diodes already installed in the junction box of each module.

In applications where reliability is important and damage likely, such as a cell-phone radio in a public park, a parallel configuration is indicated despite the advantages of a series arrangement. In this situation if one module is vandalized or stolen, the others can still contribute to the load.

If modules face off in different directions, each will have a different current depending on its exposure to sunlight, but the voltage will be more similar among the modules as long as each one is getting some light. In this situation, it is better to install the modules in parallel and let the current from each one add, than it is to limit the current to that of the one in minimum

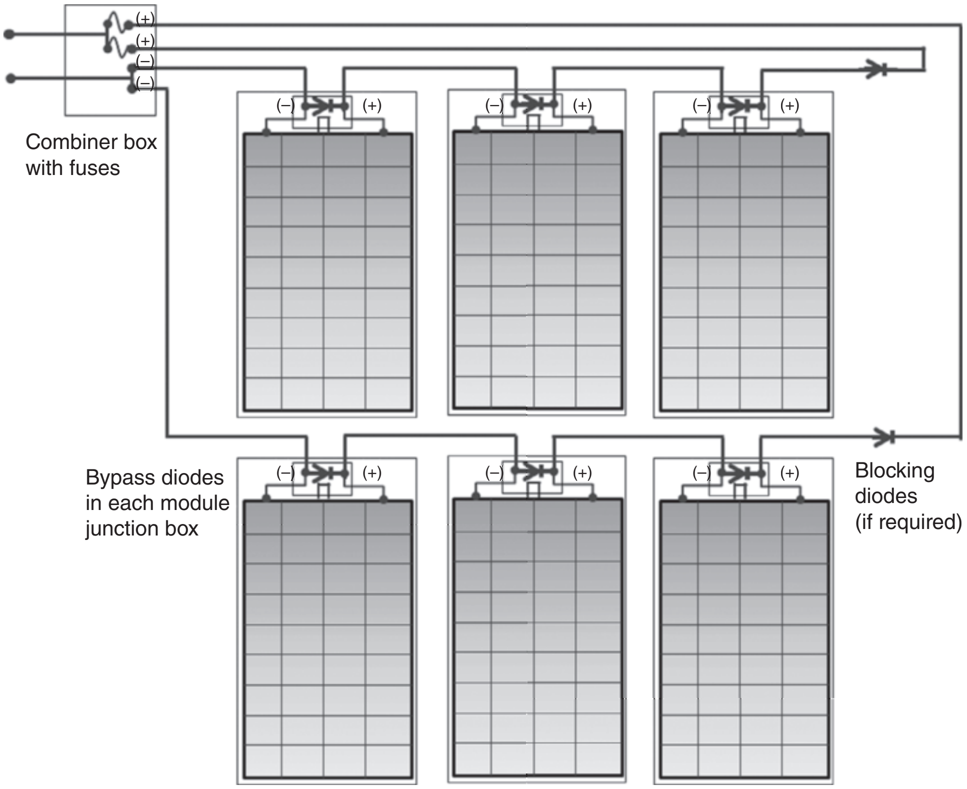

Figure 3-16. Configuration of strings with each string having three modules in series, and then the two series strings are wired in parallel. This figure also shows the location of bypass and blocking diodes. (Figure by the author)

sun. I had to take this approach in the design of an umbrella of PV modules above a picnic table, where each module faced in a different direction.

A disadvantage of parallel configuration is that if one module or series string is shaded, the higher voltage of the other modules or strings in parallel could force current the wrong way through the shaded string. "Blocking diodes" may be used to prevent this if the controller receiving the source circuits does not have this feature. Blocking diodes are common in very small, simple systems, such as yard lights, to prevent current from flowing from a battery back through the array at night. They are less common in larger systems because the diode causes a voltage drop, and associated power loss, and a more sophisticated controller provides this function.

Collector Mounting System

The forces acting on a PV array include its weight, the weight of snow on top of it, and forces applied by wind. Seismic loads may also be a consideration. The array mounting system must be able to accommodate the worst-case combination of these forces. In effort to reduce cost, the rack is being asked to provide an additional function: grounding the frames of the PV modules through the rack rather than with a separate grounding conductor to each module frame. This grounding requires that the whole rack "system" be UL-listed, and requires special hardware to make a good electrical connection by penetrating the anodized coating of both PV module frames and rack parts.

Measures may be taken by the designer to reduce loads imposed by wind on a PV array. A shallow tilt or even flat on the roof may be a good mount to reduce wind loads. Such an orientation provides good solar exposure in summer but less in winter, with the annual total being almost as good as tilt = latitude since most solar energy is available in summer. Consult the solar resource data for your location to determine the impacts of a shallow tilt angle. Wind loads may also be controlled by installing metal or plastic sheets on the back-side of the rack to keep wind from pushing up the back of the module. This approach uses the calculated aerodynamics of the wind forces to push the assembly down rather than pulling it up. With such measures to control wind loads, a "ballasted" rack becomes feasible where the rack is held down by the weight of the modules, rack, and additional concrete ballast blocks to overcome the tipping and sliding forces on the array. This leaves seismic loads as the determining loads on the design, and these are satisfied by having enough mass connected together in the ballasted rack. A ballasted system does, of course, add weight, so the roof structure must be adequate to support the weight of the whole system.

Although the weight of a PV system is often expressed as pounds per square foot (kg/m^2), it is not the average weight that is important but rather how these forces are concentrated by the rack terminations. Similarly, it is not the average wind force that is important but rather how wind forces may be concentrated. For example, wind forces may pull up on a section of the rack, and an adjacent section of the rack may also pull up on the first section. Design of the rack system must be able to transmit these concentrated forces to the building structure or to the ground.

Different PV array mounting concepts include:

- Roof mount
- Ground mount
  - Fixed tilt
  - Horizontal axis tracking
  - Pole mount
- Building-integrated PV
  - Glazing systems
  - Roofing systems
- Carport shade structure

While there are many configurations of rack parts, they all have some elements in common. PV racking systems are offered by Unirac, Direct Water and Power, Zomeworks, and other companies.

RAILS

The PV modules themselves are mounted on rails that keep all the modules of an array nice and neat in the same plane. These rails must properly support the module frame at attachment points specified by the manufacturer. The module frame must not be used to bear loads, as this will cause the module to bend and the glass to break. The rails may be fastened directly to roof attachments or to struts that support them at a steeper tilt. A splice is used to keep the rail straight where two rails are brought together, to transmit any loads, and to transmit the grounding continuity.

STRUTS

Struts connect the rails to the roof attachments or foundation and adjust to accommodate any uneven spots in the roof or foundation and keep the modules straight and true.

ATTACHMENTS TO ROOF OR FOUNDATION

Different attachment products have been developed for all different kinds of roofing (composite shingles, clay tiles, membrane roofing, built-up roofing, standing-seam metal roofing). Of these standing-seam metal roofing is perhaps the easiest to attach to because clamps are marketed that are UL-listed for attaching PV products to the standing seams of the roof. These clamps have a slot that the seam fits into and set screws which dimple, but do not penetrate, the metal seam. The array frame then attaches to these clamps (S–5! 2012). Most of the other roof types require roof attachments that do penetrate the membrane of the roof and thus must be installed with flashing to direct water flow away from the roof penetration, same as a roofer would use on a plumbing vent or flue penetrating the roof. Flexible amorphous silicon thin film modules have been adhered directly onto single-ply membrane roofs, onto the pan of standing seam metal roofs, and onto modified bitumen roofs (SolarIntegrated 2011), avoiding the need for conventional racking. SolarFrameworks provides a mount for a framed collector that integrates into membrane roofing (SolarFrameworks 2012). Clay tile is perhaps the most difficult roof to mount a PV rack on because many of the tiles need to be removed to access the roof deck and special flashing products are required to allow water to flow over the remaining tiles. Figure 3-17 is a photo of a number of different roof attachment

Figure 3-17. Attachment hardware for different roofing types including tile, shingle, membrane, and built-up roofing are described by Ron Jones and Kelli Ross of Quick Mount PV at the World Renewable Energy Congress in Denver in 2012. (Photo by the author)

types offered by QuickMount PV at a booth at a trade show in Denver in 2012.

Design of new construction would address the structural requirements of transmitting loads, but in retrofit projects the structural adequacy of the roof should be checked. The trend in new construction is to design a roof only to meet the intended loads plus a safety factor, so no additional load, not even the modest loads imposed by a PV array, may be added without reducing the safety factor. Reinforcement of the underlying roof structure is often required in these cases.

Ordinarily, rack terminations must be connected to rafters, purlins, or columns and not only to the roof deck. There are special products which do allow mounting to the roof deck by spreading a large number of attachments (screws) over a large area. A structural engineer must inspect the roof or roof plans, perform the loading calculations, and specify the type and number of fasteners for the loads (weight, wind) and allowable deflection. The structural engineer would also specify what roof structure reinforcement is necessary. The roof structure must be strong enough to support the weight of the rack, collectors, any ballast weight, and other design weight loads such as snow. But in general rack design is more an issue of holding the modules down in the wind rather than holding them up. The weight of a PV system itself may be on the order of 4 to 6 lbs/ft^2 (20 to 30 kg/m^2), whereas wind loads may be on the order of 40 lbs/ft^2 (200 kg/m^2).

In new construction, it is recommended that the architect design a section of roof with dimensions, tilt, and orientation to accommodate the collectors in the same plane as the roof for aesthetic reasons. For retrofit on an existing building, the roof may not be at the desired tilt angle or orientation. To achieve a tilt angle steeper than that of the existing roof, stanchions or standoffs hold the top of the array higher than the bottom. If standoffs are used, a minimum spacing is required between the lowest module edge and the finished roofing to allow water to drain and avoid the accumulation of debris such as leaves and twigs behind the PV modules. When mounting PV modules in the same plane as the roof it important to leave a gap of at least 5 cm (2 inches) so that air can circulate behind the modules and keep them cool.

Codes related to structural attachments include ASCE 7 "Design Loads for Building and Other Structures." ASCE 7 allows "alternative materials and methods" which solar designers exploit to optimize racks and attachements that are unique to solar energy systems (for example, ballasted racks which are held down by weight). Designers reduce wind loads by laying panels back at a low tilt angle and by adding shrouds to the back of the modules.

In order to save installation labor and avoid additional costs, many designers propose to bolt through the roof membrane directly into a rafter. I do not recommend that approach because should water penetrate the bolt hole, the rafter would be an expensive element to replace. Also the bolt hole itself weakens the rafter in a way that it was not designed for. Thus, it is recommended to use blocking or spanners between rafters and attach to those instead. It is my opinion that all roof penetrations should be flashed to properly shed water, rather than just sealed with silicone or bituminous sealant.

FOUNDATIONS

For ground-mounted collectors, the key consideration is the type of soil. Several different types of foundations have been developed, the use of which depend on the characteristics of the soil. Several of these are illustrated in Figure 3-18.

If mounted on the ground, safeguards such as a fence around the array are usually required to protect the public and to protect the array from theft or vandalism. Advantages of mounting on the ground include: avoiding the possibility of roof leaks, avoiding limits on roof structural strength, size not limited to available roof area, and safety of workers installing the system on the roof. Personal protection for workers on the roof, such as fall protection,

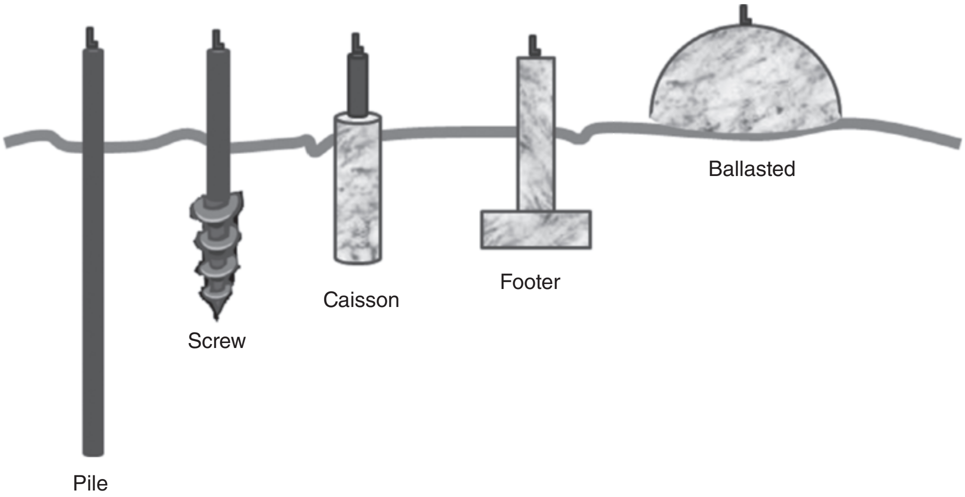

Figure 3-18. A variety of foundation alternatives are available depending on the size of the array, soil conditions at a site, and whether digging into the surface is prohibited. (Figure by the author)

adds to the installation time and cost. Disadvantages of mounting on the ground include: the land may be required for future building, the array is more visible affecting the aesthetics of the site, the array is more accessible to thieves and vandals, more wiring may be required to connect to the building electrical system.

Piles are the most common type of foundation and are usually steel pipe vibrated deep into the ground. For example, an 18 ft (6 m) long pipe may be vibrated 12 ft into the ground leaving 6 ft above ground for mounting the array to. Carport structures have become very popular because in hot sunny climates the shade on the car is appreciated to keep the car cool and comfortable and to avoid damage to the car's materials, such as to avoid cracks in the plastic dashboard. Initially, these shade structures were very expensive because they were designed by architects like a building would be. But in recent years standard designs have been introduced by companies, and by routing conductors in conduit rather than through the structural members the whole carport does not need to be UL listed, also reducing cost. Care must be taken to ensure that water and ice do not fall off the PV array onto people below; often that requires a roof deck under the PV modules. A gutter may also be required on the edge of the eve for the purpose of controlling water and ice fall.

Combiner Boxes

In a high-voltage grid-tied system, perhaps 10 or 12 or 14 PV modules are connected in series to achieve a voltage approaching but not exceeding the specified limit (600V or 1000 V_{DC}). Each of these strings would typically operate at about 450 V_{DC} depending on sunlight and temperature conditions. For each of these series strings we have one positive conductor and one negative conductor. Each of these "source circuits" is brought into a combiner box and the positive wire lands on a fuse and the negative lands on a negative busbar. The fuses holders are able to be opened without touching the fuse, enabling them to be used to open-circuit a string of modules. The other end of the fuses are connected by a busbar. The current from each of the source circuits adds on the busbar. The voltage stays the same for the combined circuit as for each of the source circuits, around 450 V_{DC} typically, or to be conservative, the minimum voltage of the source circuits. Larger conductors capable of carrying the increased current leave the combiner box to the DC disconnect. Thus the purpose of the combiner box is to combine small dimensional wires from each of the series strings to larger conductors which can make a longer run to the inverter in the building.

Maximum Power Point Tracker (MPPT)

The maximum-power point on the i-v curve is a function of insolation (current) and temperature (voltage). To match the load to optimal array voltage under changing conditions, an electronic DC to DC converter called a maximum power point tracker (MPPT) is used. A microprocessor measures voltage and current and controls a buck/boost converter (switch-resistance-inductance-capacitance circuit) that steps voltage down and current up to maximize DC power output. MPPTs do lose some power in their operation, but most should operate at 95 percent efficiency or higher. Some examples include OutbackMX60; AERL Maximizer; and RV Power Products Solar Boost. Such an MPPT might sell for around $500. This feature is often built into inverters or charge controllers.

Inverter

PV modules produce direct current (DC) at a voltage depending on insolation and temperature, but a series string of modules usually produces between 250 to 600 V_{DC} in grid-tied systems. Inverters convert this direct current to alternating current. In function the inverter is very simple- DC in, AC out. But open one up and you will see transistors, capacitors and inductors and each with a computer board (a "driver") to actuate its function. An arrangement of switches can reverse the polarity of the voltage and result in a voltage that alternates back and forth at 60 Hz or the desired frequency. Early devices were made by mechanical switching and produced a square waveform or modified square waveform.

Nowadays high-speed (high-frequency) switching is achieved by Integrated Gate Bi-Polar Transistors (IGBT). Since a transistor is just like a gate opening and closing, it doesn't increase the voltage—so an AC voltage, such as 180 V_{AC}, is dictated by the lowest voltage allowed from the array, such as 250V_{DC}. If the incoming voltage from the PV array is less than this, the inverter cannot produce the required AC voltage and the system is off, and might display a message "low voltage". The voltage on the AC side of the inverter must be maintained at a constant voltage, (V_{AC} = constant), so it is the current (i_{AC}) which varies with changing sunlight. Two-stage inverters use a diode/inductor coil upstream of the transistors to "boost" or increase the array voltage to a higher value, allowing for a higher output voltage. Of course, the other way to increase the output voltage is with a transformer on the AC side of the inverter.

A controller uses pulse width modulation to "drive" an IGBT board and deliver pulses of electric current in changing durations that approximate a sinusoidal waveform, but the waveform is jagged due to the discrete switching. Inductive coils in series on each leg smooth out some of the jaggedness, and a bank of capacitors between legs also smooth the waveform. Inductors resist sudden changes in current and capacitors resist sudden changes in voltage, thus smoothing out the waveform. Capacitors are also placed on the DC side of the IGBT to stabilize the voltage on the DC side as switching occurs.

Grid-tied inverter: The IGBTs are controlled by a digital signal processor based on the frequency as an input signal from the grid. Typical grid-tied inverters are not capable of operating without the grid (utility). IEEE and UL standards related to inverter operation require that the inverter disconnect from the utility and cease to provide power if the grid is not detected or if limits on frequency and voltage fall out of specification. They also must have "anti-islanding" to confirm that the AC waveform from the grid that they are detecting is not from another inverter or from itself. Manufacturers of these types of grid-tied inverters include Fronius, Solectria, Xantrex, Satcon, and SMA.

PV modules, and most other components such as wire, are rated for use up to either 600 V_{DC} or 1000 V_{DC} depending on the applicable standard, which limits the number of PV modules in series. However, that is 600V measured to ground, so we could have one string at +600 V and another at –600 V without either one being more than 600 V to ground. Such an arrangement is called a "bi-polar" array, and an inverter designed to use the full 1200 V of potential is called a "bi-polar" topology. This allows a higher voltage on the DC side, which allows the inverter to operate more hours of the year and reduces the need to step the voltage up with a transformer. This bi-polar arrangement requires ground-fault protection on both the positive and negative sides since either one may be un-grounded.

There are several ways in which the power conditioning required of a grid-connected PV system can be configured. Figure 3-19 shows several alternative arrangements of inverters and including some with DC to DC converters separate from the inverter.

Off-grid inverters: Instead of a grid-sensing circuit, inverters intended for off-grid use, where there is no utility, have a microprocessor with a crystal timer (like a digital clock has) that can generate a precise signal of the frequency to be produced. These generally start with the low voltage corresponding to a battery bank (12V_{DC}, 24 V_{DC}, or 48 V_{DC}), so a very high voltage rise is required of the transformer to get up to 120 V_{AC} or higher voltages, incurring losses and resulting in an efficiency that is several points lower than a grid-tied inverter. Off-grid inverters are manufactured by several companies, especially in small sizes for the recreational vehicle market.

Dual-mode inverters: An inverter that can operate either in a grid-tied mode or in an off-grid mode is called a *dual-mode* inverter. When utility power is available, they function as a grid-tied inverter. When the utility power goes out, they do disconnect from the utility circuit, so as not to energize the downed power line, but may then operate as an off-grid inverter to power dedicated circuits. At least a small battery bank is required to stabilize the voltage. Dual-mode inverters are manufactured by Outback and Beacon Power.

Inverters have nameplate peak efficiencies in excess of 97 percent, and achieve efficiency of 95 percent under typical operating conditions. The cost of an individual inverter is reported at \$0.71/W (Soalrbuzz 2012).

Definition

Advanced Inverter Features

Ordinary inverters simply take the amount of solar power available and deliver it to the grid as AC power. They have "fast clearing times" which require them to shut down immediately upon specified deviances from voltage and frequency set points. This limits the benefits that could be realized from a solar energy system when the utility is not available. "Micro-grid" strategies allow a solar generator to contribute to the load when the utility is unavailable and also to optimize economic value when the grid is available.

More sophisticated solar inverters, called "smart inverters," "programmable inverters," or "microgrid ready inverters" have been developed to address the needs of alternative financing arrangements, microgrid installations, or installation in areas of high penetration of solar energy systems (where more than 10 percent of a utility circuit load is provided by solar).

The basic capability that distinguishes these inverters is that they allow the unit to be turned off in response to an external communication signal from the utility system operator. More advanced features would include: allowing "part-load" adjustment of power output by the external communication signal (percent of power output curtailment); and both fast and slow clearing time limits in response to abnormal voltage and frequency events, in contrast to fast clearing times only for ordinary inverters (see IEEE 1547). Even more advanced features would include being able to disable anti-islanding detection for microgrid operation; power factor correction (supply reactive power); low voltage ride through (LVRT) and low frequency ride through (LFRT) to allow inverter operation in times of troubled utility operation; and a general situational awareness, including automatic transition from grid-connected to micro-grid modes.

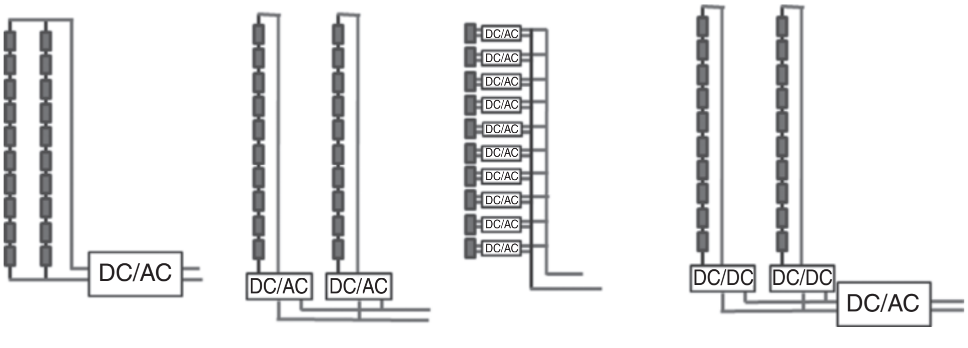

Figure 3-19. Different inverter arrangements include, from left to right: central inverter; inverter on each string; inverter on each module; dc/dc converter at each string, with central inverter. (Figure by the author)

Transformer

From the inverter discussion above we see that the voltage of the AC power leaving the inverter is limited by the lowest voltage of the array. A transformer must alter the $180V_{AC}$ typical of most inverter topologies to $208\ V_{AC}$, $240\ V_{AC}$, $277\ V_{AC}$, or $480\ V_{AC}$ depending on the voltage and configuration of phases on the AC side of the inverter.

Wiring

The PV array is generally connected with two current-carrying conductors (+ and –) and a ground wire. There are many types of wire, but only a few meet the requirements for a roof or ground-mounted PV system (National Fire Protection Association 2011). Considerations for wire selection include: ampacity (current carrying capacity); voltage rating (usually 600 V maximum for UL listing; 1000 V maximum for IEC); maximum temperature at the location; exposure to moisture; exposure to ultraviolet solar radiation; and movement or no movement (fixed or tracking). All wires should be marked with their voltage rating and their UL listing. The size of wire is indicated by its AWG number (American Wire Gauge). The smallest used for low-voltage control wires might be 24 AWG. For source circuits connecting individual modules, 12 AWG is a common size, and 6 AWG is sometimes used to connect combiner boxes. The largest AWG size is 4/0 or 0000 (pronounced "four ought") and then for sizes larger than that the convention changes to specifying the cross-sectional area of the wire. Section 300 of the National Electric Code describes the types of wire that may be used in fixed (nonmoving) type of applications such as most PV systems and prohibits the use of any other type of wire. Section 400 describes wire to be used in the movable part of a PV tracking system. These sections prescribe limits on the amount of current that a wire of a certain size can carry. The current limit depends on the type of insulation on the wire, the temperature of the application, and the number of wires in the conduit. For example, table 310 of the NEC states that 12 AWG USE-2 copper wire could carry 30 Amps if rated to 90°C, and 6 AWG of the same type wire could carry 75 Amps. There are many special conditions that reduce this rating and another section, section 240 of the NEC states that you must put a 20A breaker on the 12 AWG—thus usually limiting its current to that value regardless of the ampacity of the wire. Such details related to temperature and conduit fill require careful study for each project, since conditions may be different. Large diameter wires are expensive and difficult to install, so designers usually configure systems in such a way as to limit the current that must be carried by wires (by landing multiple smaller dimensional wires on a busbar which is better suited for large currents).

The markings on wire indicate several things;

- Type of insulation: "T" indicates thermoplastic; "R" indicates rubber; "X" indicates cross-linked polymer
- Temperature rating: "H" indicates high temperature (75C); "HH" indicates higher temperature (90C)
- Moisure: "W" indicates moisture resistant
- Other: "N" indicates nylon jacket; "–2" indicates both higher temperature (90C) and moisture resistant.

The most common type of wire to connect PV modules together is USE-2 (underground service entrance, higher temperature and moisture rating), and a special wire specific to the PV industry called PV-1 is acceptable. These wires run from PV module junction box to junction box and are not generally in conduit.

If conduit connects the junction boxes the wire must still be rated for 90C and moist conditions because the conduit is outside. Wire suitable in this situation includes any of the insulation types with a 90C and moist rating: THHN-2, THHW, RHW-2, or XHHW-2.

Within the building structure, the temperature is not expected to be high and the location is not expected to be moist, allowing other types of wire to be used within the building. THHN is perhaps most commonly specified.

WARNING

Sizing Wire Based on Ampacity and Life Cycle Cost

Ampacity is the current-carrying capacity of a wire in amps. The wire must have an adequate cross-sectional area to keep the wire from overheating. The rating of each type of wire is listed in Table 310.16 of the National Electric Code for three different temperature applications. The highest temperature (90C) relates to PV systems with components mounted outdoors in the sun. The table also further derates the listed ampacities if the temperature is higher than 30C (86F) at the location. For example, a wire rated for 25 Amps at 30C would be rated for 22.75 A at 40C (104F) and 20.5A at 50C (122F) ambient temperature. The maximum temperature experienced anywhere along the length of wire determines the ampacity required for the full length.

Ampacity of the wire is also reduced if you have more than three conductors in the conduit. The rating in the table is for three, and if you have four conductors in the conduit the rating is reduced by a factor of 0.8, and if you have 7 conductors in the conduit the rating is reduced by a factor of 0.7, and so forth. Requirements in section 690 of the NEC require that the array wiring be oversized by 1.25 times the short-circuit current to account for the fact that sunlight might be focused on the collectors by snow or clouds. General requirements in section 200 and 300 further require that all conductors be oversized by an additional 1.25 times in general.

So the task of sizing wire is to multiply the short-circuit current from a string of PV modules by 1.25 and then 1.25 again to estimate the current capacity required. Then derate the ampacity values in the table according to temperature and conduit fill, and select a wire rated to carry the required capacity.

Copper wire is expensive, so generally we would want to minimize the wire size. But larger wires have less resistance

(continued)

and less line losses, so it is advisable to do a life cycle cost analysis where both the intital cost of the wire and the cost of the additional line losses over the life of the system are bother considered. This often results in specifying a wire size that is one size larger than the minimum indicated by the ampacity requirements.

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Example Calculation of Wire Sizing

Example: Short-circuit current of a string of PV modules is 8.62 Amps. Determine if 12 AWG size of USE-2 wire typically used to connect modules is sufficient. The maximum ambient temperature is 50°C (122°F) and there are 8 conductors in the conduit. Assume the applicable standard is the National Electric Code.

$$\text{Required Ampacity: } (8.62\text{A})*(1.25)*(1.25) = 13.5\text{A}$$

The 12 AWG wire chosen to connect the modules is rated for 30A at 30C. To know all the details of the applicable codes is important. The lesson of this example is that another section of the NEC, Section 240, states that 12 AWG must have at most a 20 A breaker or fuse on it. So instead of 30A, we are limited to 20A, but that's okay because at the end of this example we are going to put a 15A fuse on it anyway.

At 40C (104F) the temperature derate factor from NEC Table 316.10 is 0.82, and thus the maximum current of our 12 AWG wire is 24.6A at 40C. For 8 conductors in the conduit the derating is 0.7, so the ampacity of the 12 AWG wire is reduced to 17.2 A. Even though the rating of the wire is almost half its value listed before derating, 17.2 A capacity is greater than 13.5A needed so the specified wire is sufficient in size. Since we expect the maximum current to be 13.5A, we protect the conductor with a 15A fuse typical of PV source circuits.

Grounding System

There are three purposes served by the grounding system: *equipment ground*, *equipment bonding*, and *grounding electrode*.

> Equipment ground: All module frames, array support structure, metal enclosures, panels, inverter cabinet, and metal conduit—really any exposed metal parts of the PV system—are fitted with "grounding lugs" that ensure a continuous electrical connection from the metal part to ground. The grounding lugs are then connected with a common grounding conductor, usually bare copper wire, which terminates at the ground rod (long metal rod pounded into the soil, or other effective connection to the earth). This serves as an equipment ground, which prevents voltage due to lightning or contact with other sources of voltage.
>
> Equipment bonding: This grounding system also serves as equipment bonding, so that if any of the metal parts comes in contact with the voltage existing in the system (such as insulation on a wire getting chewed by a mouse), there is a path for the current to flow through and trip the circuit breaker rather than for the metal part to stay energized until somebody touches it.
>
> Grounding electrode: The grounding system also serves as the grounding electrode in the wiring system. The negative wire of the DC circuit is often grounded, but in bi-polar arrays, the negative of one half of the array is grounded and the positive of the other half is grounded (Wiles 2010). Thus the "center-tapped" conductor of a bi-polar array is grounded. Another exception is the back-contact PV modules manufactured by Sunpower, for which the positive conductor is grounded. On the AC side of the system, the neutral wire of the inverter output is grounded. In some inverter designs the negative side of the DC circuit and the neutral of the AC circuit might share a grounding connection. The purpose of this grounding electrode is to stabilize voltage under normal operation and is important for the proper operation of many inverters, and generally the grounding terminal of the inverter is connected directly to the ground rod.

Grounding Rod

The grounding system often uses one or more long conductive rods pounded into the ground directly adjacent to the solar energy system to form the electrode for the grounding system. In order to prevent current from flowing through the grounding system, there must be only one connection to ground for the current carrying conductors of a system, or if more than one, they must be directly bonded together. The number and locations of grounding rods corresponds to the size and configuration of the array and balance of system components. Refer to the requirements of applicable codes and standards (National Fire Protection Association 2011).

Ground Fault Current Interrupter (GFCI)

This device disconnects the source of power if it detects a current to ground, which would indicate a fault. They protect against array wiring that has shorted to ground. For example a squirrel might chew the insulation off a wire that then comes in contact with the grounded module frame. The GFCI has a sensor that disconnects the power circuit if it detects current in the ground circuit. This prevents an electrical arc from forming and starting a fire.

Conduit

In "readily accessible" parts of a PV system it is required that conductors be enclosed and protected (National Fire Protection Association 2011). Often the wires that connect the PV panels together are not in conduit in a ground-mounted

Concept

"Bi-Polar" PV Systems

A PV system may be designed in a "bi-polar" configuration, which means that half of the combiner boxes are wired positive with respect to ground, and the other half are wired negative to ground. In the half wired positive with respect to ground, a pair of wires from each string of PV modules in series enters the combiner box and the positive wire of each pair is attached to a fuse, and the other sides of all the fuses are bussed together and to the positive wire leaving the box. The negative wires of each source circuit pair are bussed together and to the negative wire leaving the combiner box and the ground wire is attached to this same negative bus. In the half wired negative with respect to ground, the negative wires are fused and the positive wires from each source circuit are grounded. The fuse is not on the grounded side because, should a fault occur, a blown fuse will not disconnect the source of voltage from ground. Of course, the inverter has to be designed to accommodate this bi-polar configuration, with a center-tap that is grounded rather than the negative. The reason designers often use a bi-polar configuration is that it allows each series string to be within the limit of 600V with respect to ground imposed by code and the UL-listing of the components, but the voltage difference available to the inverter is twice that: $+V_{mp}$ on the positive side and $-V_{mp}$ on the negative side.

system, and thus the system should have a fence around it so that the wires are not readily accessible to the public. Code requires that all wires within the structure (building) be in conduit. Even where it is not required, I recommend that wires be protected by conduit or other wire "raceway." This is for several reasons: the voltage, commonly up to 600V or 1000V, presents a hazard should the wire be unplugged or cut into; the wires and electrical connections could be damaged by pulling on them; and the copper itself is valuable and a temptation for thieves. A wire raceway could be created by running a tray down the back of the array to lay the source circuit wires in, thus protecting the wires and the public. Like all metal parts this tray must be properly grounded. Metallic conduit is the type most typically used in PV systems, due in large part to the sunlight (ultraviolet degradation of plastics) and the physical stresses of outdoor use.

DC Disconnect

The DC disconnect is specialized in that it must be able to interrupt the DC current and withstand the resulting arc that forms. Specific labeling requirements are written in the code so that the disconnect can be easily found and operated by those not familiar with the system (emergency personnel).

AC Disconnect

Since the arc associated with AC current extinguishes itself 60 times per second (or 50Hz in Europe), a standard disconnect of the type available at a local electrical shop is sufficient for use as the AC disconnect. The AC disconnect must be labeled as specified in codes so that it may be easily found and turned off in an emergency.

Batteries

In off-grid systems, batteries are required to store charge for when the electricity is needed. The battery industry is large, with markets in all kinds of consumer and industrial applications. Many battery manufacturers have developed products with features specifically designed for solar applications. Types of batteries considered in solar applications include flooded lead-acid; sealed lead acid (valve regulated, VRLA); nickel cadmium (NiCd), and lithium ion (Li-ion). The open design of flooded batteries makes it easy to test and maintain the electrolyte, thus optimizing efficiency and lifetime. If frequent battery maintenance is not possible or affordable, valve regulated (VRLA) or absorbed glass mat (AGM) batteries do not require maintenance of the electrolyte. I recently compared two lead acid batteries and NiCd with the following results for an application that requires 200 kWh storage at 24 volts:

- Small VRLA; 2,000 Ah per cell; 8 strings of 12 cells each; cost \$73,000; Nominal Capacity 384 kWh; Effective Capacity 230 kWh: Calculated Life 16.2 years; Cost per kWh stored \$0.070.
- Large VRLA; 4,800 Ah per cell; 3 strings of 12 cells each; cost \$110,000; Nominal Capacity 340 kWh; Effective Capacity 207 kWh: Calculated Life 16.8 years; Cost per kWh stored \$0.072.
- NiCd: 1054 Ah per cell; 10 strings of 22 cells each; cost \$243,000; Nominal Capacity 274 kWh; Effective Capacity 219 kWh: Calculated Life 12.8 years; Cost per kWh stored \$0.149.

While more sophisticated alternatives are available, the projects that I've been involved in all selected lead-acid batteries based on the maturity of the technology, the high efficiency, and the low cost. Lead acid batteries for PV applications may include such features as thicker lead plates, special metallurgy to improve the plates, and an extra reservoir of electrolyte in the top of the battery jar.

Lead-acid batteries come in 2-volt cells, a number that is set by the battery chemistry. Any number of cells may be connected in series "strings" to achieve the desired voltage. It is difficult to equalize charge among batteries in parallel, so designers usually specify very large 2-volt cells in series. However, it is advisable to have at least two parallel strings of batteries so that some storage and operation of the system is possible while one of the battery strings is down for maintenance or replacement. Each of these series strings could have its own charge controller to maximize battery life.

Batteries incur very significant cost in terms of initial cost, maintenance requirements, safety requirements, environmental liabilities, and short service lives. Building owners installing battery systems must consider the responsibility and try to minimize battery size by scheduling and controlling loads, and managing generation resources, so that the need for electric storage is minimized. And then exercise stewardship in maintenance and recycling of the batteries that are required.

Manufacturers of batteries for PV applications include Deka, Crown, East Penn, GNB Technologies, Optima, Rolls, Trojan, US Battery, and Yuasa in the US; Surrette in Canada; Deta in the UK, EBC in Korea, First National in South Africa; Shenzhen in China; Banner Batterien of Austria; Accu Oerlikon of Switzerland; Sonnenschien in Germany; and Tovarna in Slovenia. The cost of batteries depends on the size and type, but is reported at $239 to $260/kWh of storage capacity. Premium quality industrial lead acid batteries may be as much as $381/kWh (Solarbuzz 2012). Batteries with other chemistry such as Li-ion or NiCd may be as high as $1000/kWh of storage capacity.

For most types of batteries, the power delivery (kW) and the energy storage (kWh) both increase proportionally as we add more batteries. But "flow batteries" have been introduced that store the reactants in tanks (the energy storage, kWh) separate from the reactor (the chemical to power reaction, kW), and thus allow addition of kWh storage without needlessly increasing power output. This would be an advantage for solar because a lot of energy storage (kWh) is needed to serve a load for days without sun.

Charge Controller

If we have batteries in a system, we must have a charge controller to regulate the charging of the batteries according to the type of battery.

Charge controllers are relatively simple devices, and there are a lot of suppliers. Manufacturers of charge controllers include Apollo, ETA Engineering, Bejing Epsolar in China, Costs are reported at $5.92 per amp of charging current (Solarbuzz 2012).

Low-Voltage Disconnect

Similar to the charge controller, the low-voltage disconnect is required to protect the batteries. If the voltage of the batteries reaches a low setting, say 11.7 volts for a 12-V battery, it will open-circuit the load. It seems like a terrible thing to disconnect the load, but if you don't, the battery will have a short lifetime and the load will be interrupted anyway.

Automatic Generator Start/Stop

When the batteries reach a set point voltage or state of charge, an automatic generator starter will try to start the engine of a diesel or propane-fueled generator. This device is programmable regarding the number of seconds it will turn the starter motor and the number of times it will try. Once the generator starts, the generator serves the load and powers a battery charger. When the batteries are charged up to a prescribed voltage, the controller turns the generator off and the load is served from the battery/inverter again. I think these control circuits sell for about $100.

Automatic Transfer Switch

When the generator starts to deliver power, an automatic transfer switch transfers the load from the inverter to the generator. These switches generally break the connection to the inverter before they make connection to the generator, so there is a momentary interruption of electric power to the load, which may cause problems in electronics such as clocks and computers. More sophisticated system topologies are available which can act as uninterruptible power supplies, but they add significantly to the cost of the system and reduce efficiency, so that usually the recommendation is to use a simple transfer switch on the overall power system and then use a small uninterruptible power supply for individual computers or critical loads, and get an alarm clock with a back-up battery in it.

ESTIMATING THE COST OF A PHOTOVOLTAIC SYSTEM

Initial Cost Estimate

The cost of photovoltaic systems has come down dramatically in recent years due to three factors:

1. Technical developments in device efficiency and manufacturing technology;
2. Economies of scale in the burgeoning market, better factory utilization and through-put, and vertical integration eliminating multiple layers of overhead and profit; and
3. China.

Back in the 1950s and 1960s, Hoffman Electronics was selling PV devices for as much as $\$1,500/W_{STC}$. The lowest cost I've heard recently is a multicrystalline module imported into the United States from China at a cost of $\$0.87/W_{STC}$. Figure 3-20 shows how prices have come down since 1975. Cost dropped dramatically until 2004, when the PV industry outgrew the silicon refinery capacity that it shared with the electronics industry. Silicon is one of the most common elements on earth, but it must be refined to a very high purity, and a shortage of refinery capacity was driving prices up. By 2007 refiners had built silicon refineries especially for solar, and with the introduction of US tax credits in 2005, an economy-of-scale has been driving costs down since that year. The PV business is very competitive. New entries with lower module costs are putting older companies out of business, despite the great technological contributions and sound business management of these older companies.

Table 3-6 lists reported costs for different types of PV modules. While average "full blown retail price" of a single PV module averaged $2.29 in March of 2012, about a third of suppliers price their modules at less than $2.00/W. In March 2012 the lowest single-crystal silicon PV module price was $1.10/W;

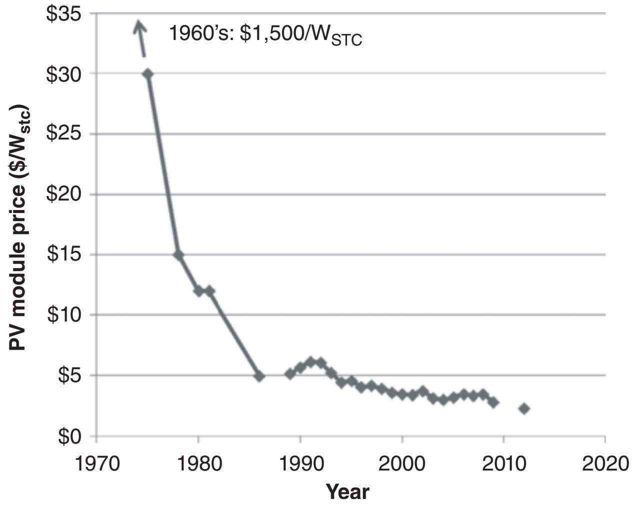

Figure 3-20. The price of PV modules has declined significantly from 1975 to 2011. (Figure by the author, data from DOE (US Energy Information Administration 2011a) and 2012 from Solarbuzz (2012)

the lowest multicrystal PV price was $1.06/W; and the lowest thin-film price was $0.84/W (Solarbuzz 2012).

Prior to detailed design it is necessary to take a heuristic approach to estimate the cost of a PV system: how much did it cost last time? Subsequently, as the detailed design develops, a detailed cost estimate may be prepared with each piece of hardware and installation task itemized. The installed cost of the PV system, including all costs to provide a complete operational system—overhead, profit, design, and any other costs related to the project—is given the symbol $C_{initial}$ in the simple economic calculations to follow.

Heuristic Cost Information

The US Department of Energy Solar Energy Program has focused a lot of research recently on the costs of a PV system and how that cost might be brought down to the point where PV can compete with more conventional sources of energy without public incentives. In 2011, DOE produced the “Sunshot Vision Study” to inform program planning toward this goal. Table 3-5

TABLE 3-5. COSTS BREAKDOWN IN UNITS OF $ PER WATT RATED STC FOR COMPLETE PV SYSTEMS IN DIFFERENT MARKET SEGMENTS FROM DOE SUNSHOT VISION STUDY, 2010 BENCHMARK COSTS

Component/type	Residential rooftop (5 kW)	Commercial rooftop (215 kW)	Utility groundmount-fixed tilt (>20 MW)	Utility groundmount-1-axis tracking (>20 MW)
PV modules	$2.15	$2.05	$1.95	$1.95
Mounting rack	$0.30	$0.30	$0.20	$0.45
Inverter	$0.42	$0.37	$0.29	$0.29
Tracking mechanism	$0	$0	$0	$0.62
Combiner boxes	$0.02	$0.02	$0.01	$0.01
Meter	$0.02	$0.04	$0	$0
System monitor	$0.09	$0.03	$0	$0
AC, DC disconnects	$0.01	$0.01	$0	$0
Fuses and holders	$0.01	$0.01	$0	$0
Wire and conduit	$0.02	$0.02	$0.16	$0.16
Electrical labor	$0.30	$0.18	$0.13	$0.13
Other hardware labor	$0.33	$0.31	$0.07	$0.07
Permitting	$0.08	$0.23	$0	$0
Grid connection	$0.30	$0.01	$0.01	$0.01
Land cost	$0	$0	$0.04	$0.04
Land preparation	$0	$0	$0.20	$0.20
Materials markup	$0.89	$0.55	$0.31	$0.31
Sales tax	$0.26	$0.21	$0.21	$0.21
Overhead	$0.34	$0.16	$0.06	$0.06
Profit	$0.19	$0.10	$0.13	$0.13
Total C_{intial} \$/WSTC	**$5.73**	**$4.60**	**$3.77**	**$4.64**

Sources: Goodrich, Woodhouse, and James 2011.

TABLE 3-6. HEURISTIC UNIT COSTS OF PV MODULES BY TYPE OF PV DEVICE EMPLOYED

Collector type	Average
Silicon crystal	$2.94
Silicon multicrystal	$2.44
Silicon thin film	
Cadmium telluride	$1.03
CIGS	$0.68
Concentrator	$0.68
Average	$2.29

Sources: EIA 2010; Solarbuzz 2012.

reports the study's cost breakdown for the 2010 benchmark (Goodrich, Woodhouse, and James 2011; DOE EERE 2012).

While these costs are derived from actual project data, they are low compared to my experience. In addition to the size of the system, costs also vary depending on the type of the system, the details of the installation, and the geographic location. General labor and materials also vary by location, and a good source of cost data are the City Cost Adjustment Factors for electrical costs in different cities published in RS Means cost-estimating manuals (RS Means 2011). For example, Means reports that the cost of electrical work varies from 60 percent of the national average in Guymon, Oklahoma, to 143 percent of average in Flushing, New York. Most of the difference is in labor costs ($/hour for installing electrician); hardware costs vary only from 90 percent to 110 percent.

Empirical data may also sorted by the type of schematic diagram employed by the system (Table 3-7). Direct-drive systems are less expensive because they don't employ a battery or inverter. These costs should be considered minimum for hardware and installation and cost related to any site-specific circumstances would be additional.

And then based on some simple calculations, I can offer a per-square-meter (per sf) cost opinion on the different mounting systems (Table 3-8).

By looking across this heuristic data, we can extract a rule of thumb: that $5/watt is a reasonable cost expectation for a grid-tied solar photovoltaics system and $12/watt for a system with batteries. But site-specific considerations may make this much higher. On the high end for example, an off-grid system on a Pacific island has cost $17/watt and an aesthetic integration into a building façade has cost $25/watt.

TABLE 3-7. HEURISTIC UNIT COSTS OF COMPLETE PHOTOVOLTAIC SYSTEMS AS A FUNCTION OF TYPE OF SYSTEM SCHEMATIC DIAGRAM

System type	Average
Direct drive	$3.82
PV/battery	$10.28
PV/battery/inverter	$11.47
PV/inverter	$5.02

Sources: EIA 2010; Solarbuzz 2012.

Detailed Cost Estimate

After the schematic design establishes the detail of the design, it is possible to do a detailed cost estimate. The detailed cost estimate itemizes each component, and the installation labor associated with each component or the PV project as a whole. Adders account for overhead, profit, or any other cost adders that can be considered "percent of project." Cost-estimating manuals published by RS Means are an excellent reference for detailed cost estimates (RS Means 2011). Grid-tied and off-grid PV systems appear in *Electrical Cost Estimating, Green Building: Project Planning and Cost Estimating,* and the *Green Building Cost Data* books, for example (RS Means 2011).

In order to present an example of a detailed cost estimate we consider a grid-tied PV systems consisting of 621* $240W_{STC}$ PV Modules for a total rated STC power output of 149 kW (Table 3-9). Such a system would require about 1,000 m^2 (10,800 sf) of rack area. For each component, we estimate the hardware and the installation cost. This information is obtained from cost-estimating manuals (RS Means 2011), by searching for products for sale on-line, and by contacting suppliers.

TABLE 3-8. COST PER UNIT AREA OF SOLAR COLLECTOR FOR DIFFERENT TYPES OF ROOF AND GROUND MOUNTING SYSTEMS (MOUNTING ONLY, NO ELECTRICAL)

	Material cost per sf ($/sf)	Labor cost per sf ($/sf)	Equipment rental cost per sf ($/sf)	Total cost per sf ($/sf)	Total cost per m^2 ($/$m^2$)
Rack structure	$3.00	$5.00	$0.10	$8.10	$87
Factory lamination to roof material (BIPV)	$9.50	$0.00	$0.00	$9.50	$102
Pole mount earth foundation	$11.84	$7.42	$0.83	$20.09	$216
Parking structure including columns	$21.84	$15.00	$0.83	$37.67	$405

TABLE 3-9. EXAMPLE COST-ESTIMATE FOR 149 KW GRID-TIED SOLAR PHOTOVOLTAIC POWER SYSTEM

	Number of units	Unit	Material cost per unit ($/unit)	Labor cost per unit($)	Equipment rental cost per unit ($)	Total
PV modules; 240 W; V_{oc} 36.9V; I_{sc} = 8.62A; 14.8% efficient	621	each	$300	$100	$80	$298,080
Array DC electrical						
Array connectors; 6′ length 10AWG; UV resistant; weatherproof; locking connection	621	each	$28	$10		$23,598
Array connectors; 30′ length 10AWG; UV resistant; weatherproof; locking connection	20	each	$54	$15		$1,380
Array connectors; 50′ length 10AWG; UV resistant; weatherproof; locking connection	20	each	$68	$20		$1,760
Array connectors; 100′ length 10AWG; UV resistant; weatherproof; locking connection	20	each	$120	$40		$3,200
Combiner box; 2- source circuits; fuse holders	4	each	$100	$100		$800
Mounting bracket for Combiner box	4	each	$36	$60		$384
Fuse holder: touch safe	41		$6	$12		$756
Fuses 600Vdc; 15A	41	each	$3	$5		$328
Grounding electrode	10	each	$25	$45		$725
DC disconnect	1			$240		$240
AC electrical						
Utility connection box	1	each	$450	$180		$630
Inverter	1	each	$60,000	$180	$280	$60,460
Grounding electrode	1	each	$25	$45		$70
AC disconnect	1	each		$100		$100
Isolation transformer	1	each	$18,500	$745	$280	$19,525
Meter	1	each	$500	$600		$1,100
Wire	600	Ft	$4	$25		$17,400
Conduit with fittings and supports	200	Ft	$3	$25		$5,600
Mounting system						
Rack rails, 13 ft long, 150 mph; exposure category B; 60 aluminum	200	each	$100	$60		$32,000
Rail splice	199	each	$36			$7,164
Roof attachments; 6″ clearance; tilted steel standoff;	400	each	$24			$9,600
L-foot roof attachment	400	each	$13			$5,200
Module clamps; stainless steel	1,400	each	$15			$21,000
Roofing supplies and labor (subcontract)	400	each	$45	$65		$44,000

(continued)

TABLE 3-9. ***(Continud)***

	Number of units	Unit	Material cost per unit ($/unit)	Labor cost per unit($)	Equipment rental cost per unit ($)	Total
Fixed costs						
Design consultant						$5,000
Design engineer of record						$15,000
Project management						$15,000
Permit processes						$500
Utility interconnect agreement						$500
Interpretive display						$8,000
Compliance process management						$4,000
Escalation to middate of construction (4%)						$24,131
Overhead						$22,880
Profit						$14,300
Sales tax						$31,370
					Total	$695,950
					Average $/W	$4.67

In conclusion, our detailed estimate of $695,950 for a 149 kW PV system averages $4.67/W$_{STC}$ (Table 3-9), which is very close to our simple heuristic estimate of $6.41/W$_{STC}$ for a commercial rooftop PV system in Table 3-5.

ESTIMATING ELECTRIC USE AND SOLAR FRACTION

Utility Bills

If you are considering adding PV to an existing building, the utility bills or more detailed measurements of the electricity use of the building are often readily available. Some utilities provide a lot of detail regarding time-of-day that the building uses electricity and weekdays versus weekends, but on the other hand sometimes all we get from the electric bill is the monthly total energy consumption (kWh). Detailed analysis using computer simulation uses a 1-hour time interval, and a 15-minute interval is recommended to really mimic the details of a demand ($/kW) charge. Hourly or even 15-minute load data may be available as an information service offered by the utility, or by processor of utility data other than the utility, or may be ascertained by sub-metering.

Building Energy Model

However, such metering takes time to collect, and describes only what the load was doing during the monitoring period. Modeling is often used to predict loads under different conditions, or to predict what the electric load is in a building before it is built or before a major renovation. An easy-to-use building energy modeling tool is EQuest (Hirsch, 2009). It has fill-in-the-blank type interfaces and default building types. Often, I just start with a default building type and change only the square footage; number of floors; aspect ratio (north-south to east-west); mechanical system type; utility rates; and location. The state-of-the-art in building simulation is EnergyPlus (EERE 2011). I've sat through the training twice but have yet to use it—looks pretty involved, but a number of available interfaces make it easier to use. Any of these building models can output an hourly electrical load for your solar analysis.

Calculate Loads

For grid-tied systems, the inverter is sized to meet some fraction of the STC rating of the PV array, say 95 or 100 percent. For off-grid systems, the inverter is sized to meet the peak load. Different types of devices use different amounts of electric current and at different voltages. Electric use varies dramatically and includes effects of climate, demographics, and occupant behavior. The total power required of a PV system is that required to deliver a peak amount of electric current and that required to compensate inefficiencies in the batteries, inverter, and other balance of system components. For N different electrical devices

$$P_{\text{load, max}} = \sum_{i=1}^{N} [i_{\text{load},i} v_{\text{load},i} / \eta_{\text{bos},i}] * (\text{diversity factor}) \quad (3\text{-}30)$$

Where $i_{load,i}$ is the current draw from a device i, $v_{load,i}$ is the desired delivery voltage for device i. The "diversity factor" recognizes that not all of the devices will be on at their full power all the time, but would be 1.0 for a set of devices all of which indeed could be on at the same time $\eta_{bos,i}$ is any efficiency specific to device i, which is usually 1.0 but may be less if there are long line losses to a load or losses in a transformer or rectifier feeding only that load device. This is not to be confused with the η_{bos} of the PV system (battery, charge controller, inverter, etc) but in addition to it. So the difference is that $\eta_{bos,i}$ is the efficiency associated with serving each load i, whereas $\eta_{bos,}$ is the efficiency of the components of the solar energy system. For example, if a DC device was powered off the battery, the balance of system efficiency would be 0.80 for the round-trip efficiency of the battery charge/discharge. If the device is also AC powered through an inverter of 90 percent efficiency, then the balance of system efficiency for that device would be (0.8 battery efficiency*0.9 inverter efficiency) = 0.72 bos efficiency. In practice, 0.77 is often taken as balance of system efficiency for a grid-tied system and 0.60 is a common assumed value for off-grid systems with batteries.

It might be feasible for PV to deliver and a battery to store a single day's worth of electrical energy. Thus, calculations often tally electric use on a daily basis (kWh/day). The energy consumed is the power of each device multipled by its "on-time" each day.

$$E_{load} = \sum_{n=1}^{N\text{ devices}} i_{load,i} v_{load,i} \; / \; \eta_{bos,i} \;\; \Delta t_i \qquad (3\text{-}31)$$

Where Δt_i is the number of hours each day that device i is "on."

REFERENCE

Balance of System Efficiency (η_{bos})

The amount of energy generated by the PV system must be enough to power not only the load but also the inefficiencies in the PV system itself. An efficiency for the entire system is calculated by multiplying all the individual efficiencies together. A good reference for balance of efficiency values are the default values for the PV Watts computer program (NREL 2011), listed in Table 3-10, with the resulting value of balance of system efficiency η_{bos} of the entire system.

TABLE 3-10. DERATING FACTORS MULTIPLIED BY POWER AND ENERGY DELIVERY TO ACCOUNT FOR INEFFICIENCIES IN THE BALANCE OF THE PV SYSTEM AND DIRT ON THE PV MODULES

Component derate factors	Efficiency (PVWatts default)	Range
PV module nameplate DC rating	0.95	0.80–1.05
Inverter and transformer	0.92	0.88–0.98
Mismatch	0.98	0.97–0.995
Diodes and connections	0.995	0.99–0.997
DC wiring	0.98	0.97–0.99
AC wiring	0.99	0.98–0.993
Soiling	0.95	0.30–0.995
System availability	0.98	0.00–0.995
Shading	1.00	0.00–1.00
Sun-tracking	1.00	0.95–1.00
Age	1.00	0.70–1.00
Overall balance of system efficiency, η_{bos}	0.77	

For an off-grid system, all of these factors might apply, plus we could account for an 80 percent round-trip efficiency of the battery charging/discharging (Table 3-11).

TABLE 3-11. ROUND-TRIP EFFICIENCY OF BATTERY AND OVERALL SYSTEM EFFICIENCY FOR AN OFF-GRID SYSTEM WITH BATTERIES

Component derate factors	Efficiency
Battery round trip	0.80
Overall balance of system efficiency, η_{bos}	0.62

Simple Heuristic Load Estimate

The benchmark for electricity use in commercial buildings is 120 kWh/m^2/year (11 kWh/sf/year) for most areas where heating is provided by other fuels and 196 kWh/m^2 (18 kWh/sf/year) in areas where air conditioning is required (Sharp 1994). A typical building may have an electric demand on the order of 50 W/m^2 (5 W/sf) during the day from 7:00 a.m. to 6:00 p.m. and 5 W/m^2 at night. Solar radiation on a horizontal roof varies from about 1,000 kWh/m^2/year (100 kWh/sf/year) in Washington State west of the Cascade Mountains to about 2,000 kWh/m^2/year (200 kWh/sf/year) in the desert of south-central California. This provides a conclusion that we can draw even before more detailed information is available: if we could achieve an efficiency of 11 to 18 percent for the photovoltaics, the roof area of single story buildings such as residences, light commercial, warehouses, etc. would generally be sufficient to accommodate enough PV to offset the annual energy use of the buildings. Multi-story buildings that have strived for net-zero utility energy use have had to put PV on adjacent ground mounts, such as parking shades, to obtain the required surface area.

TIP

Efficiency First

Almost all energy efficiency measures are more cost-effective than buying PV to serve that load. Based on some projects at National Park Service facilities, one dollar spent on more efficient lighting saves \$6 off the cost of the PV to power it, and spending \$1 on more efficient refrigeration saves \$2 off the PV. An EIA August 2011 press release cites \$1 spent on efficiency saves \$2 off the PV.

Changes to occupant behavior could results in a drastic and sudden reduction in building electric use. It's my guess that energy use could be reduced by 40 percent if occupants were as fanatical about saving electricity as they are about recycling and casual Friday.

- Many upgrades of lighting and control systems can offer savings.
- Replacement of aging mechanical systems often results in savings.
- Upgrades to transformers and building distribution system may result in savings.

Although building upgrades cost money, they are almost always less expensive than the purchase of a photovoltaic system to provide the amount of power saved.

Experience with energy audits indicates that an energy audit easily identifies 15 to 25 percent savings in electricity, but implementing projects can be challenging. Still, statistics tracked by government agencies prove that efficiency savings are achievable and persistent (FEMP 2011).

RECOMMENDED APPLICATIONS

Off-grid Applications

Even though the market for grid-tied PV systems has far outgrown that of off-grid applications, the remote loads still offer the highest rewards. PV in an off-grid application replaces primary batteries or generators that cost a lot to operate, require a lot of maintenance, and have a lot of environmental impact and impact on site operations, and raise safety and environmental health concerns For example, I added up costs for fuel, fuel delivery, air filters, oil filters, oil changes, and engine overhaul and calculated \$1.68/kWh electricity cost associated with a 7-kW propane-fueled generator at a campground entrance station in Pueblo, Colorado.

Compared to primary batteries or generators, PV is able to provide on-site power, delivered free by the sun to even the most remote locations, with no noise and no on-site emissions. The financial, environmental, and operational benefits are compelling.

A new utility connection can cost a lot of money. A new power line extension can cost at least \$17,000/mile over flat land, but there seems to be no upper limit on how much a new line might cost. For example, helicopter construction over a mountain range might cost \$1million per mile. To this the utility often adds a considerable charge to install a transformer, meter, and establish a new utility service and account, often on the order of \$10,000. An autonomous PV system to serve a small load may be a less expensive alternative.

This extends to small loads even in an urban environment. For example, it would be cheaper to power an irrigation control valve in a road median with PV than it would be to drill under the road to install a wire to the median. There are thousands of similar small applications all around us (cell-phone towers; wi-fi boxes; parking meters; directional signage; telephones; and many, many more).

Residential

Homeowners see PV as an investment, and most are attracted to a financial rate of return. Still, grass-roots marketing campaigns based on the environmental attributes have also been successful. A PV system can result in substantial savings off the electric bill, and many homeowners are motivated by tax credits and utility rebates.

There are some advantages and disadvantages regarding residential PV. Many houses are not occupied during the day, with the occupants at school and at work. Thus the PV-generated electricity would be received back into the utility system. There are limits to this "net- metering" that occur when too many houses on a utility circuit install PV, and extra power generated by the PV has no load to serve on the local utility circuit. However, PV has perhaps its highest value of energy cost savings in residential where the rates are higher than commercial or industrial rates. Most utility policies are friendly to small residential systems, and the simple rate structures common of residential customers tends to put a higher value on the PV energy than more detailed rate schedules typical of commercial and industrial buildings.

Commercial Buildings

Commercial buildings are good applications for PV because they use power mostly during the day, thus actually reducing the load on the utility. Commercial buildings often have expansive roofs which provide a site for a PV system large enough to meet a substantial part of the building electric requirement. Many commercial buildings are heated by the busy people and computers inside, and so solar output is coincident with loads on the building cooling system, thus reducing the "peak demand" (kW) of the building and maximizing the economic benefit of the PV. On-site PV systems can also enhance the sustainability or corporate ethics image that a building owner may promote.

Industrial Buildings

Industrial buildings enjoy the lowest utility rates, but they may also have large roof areas or buffer land areas that may be used for PV. Energy is often a large fraction of a factory's operating cost, so if incentives and tax credits are sufficient, industrial sites offer good candidates for very large PV systems. These large projects enjoy a low $/kW cost of the PV due to the economies of scale and negotiating clout of the factory owner. Industrial customer classes generally pay the lowest utility rates, and pay rates based on complicated rate schedules which often value the solar energy at a rate lower than the average per kWh rate.

SIMPLE HAND CALCULATION OF PHOTOVOLTAIC SYSTEM SIZE AND ENERGY DELIVERY

The size of a PV system is best determined by optimizing life-cycle cost, and satisfying other criteria, evaluated by a computer program that takes into account details of a load and a design. However, we must estimate at least a preliminary size before a design is created, and this may be accomplished by simple hand calculation. Sizing the components of a PV system is different depending on whether it is an off-grid or grid-tied system:

Off-grid PV system sizing: Often, only one or two days of battery storage is feasible, and the PV array as the only energy source has to generate enough energy on a short winter day to meet the load. Thus the sizing strategy is to divide the daily load $E_{\text{load,day}}$ (kWh/day) by the minimum solar resource $I_{\text{C,min day}}$(kWh/m^2/day). This implies that we have at least one day's worth of battery storage, so that solar incident only during daylight hours meets the total load over the 24-hour day. The size of the solar collector area required to meet the load on the shortest days is

$$A_C = \frac{E_{\text{load,day}}}{I_{\text{C,min day}}\eta_{\text{solar}}\eta_{\text{bos}}\,\text{degr}} \tag{3-32}$$

Where A_C = collector area (m^2); η_{solar} = efficiency of the PV array; η_{bos} is the balance-of-system efficiency; and *degr* is the degradation due to age. $I_{\text{C,min day}}$ is the minimum daily resource value (kWh/m^2/day) expected over the course of the year, usually in January for northern hemisphere and June in the southern. In other seasons, the PV array would be larger than that required to meet the load and excess energy would be wasted. If we consider the efficiency of the solar to be that measured under standard test conditions (STC), then this calculation can also be made to result in the rated power of the PV array, P_{STC} (kW) = (1 kW/m^2)*A$_c$*η_{STC}.

$$P_{\text{solar}} = \frac{E_{\text{load,day}}}{\left[\dfrac{I_{C\text{ min,day}}\eta_{\text{bos}}}{\left(1\dfrac{kW}{m^2}\right)}\right]} \tag{3-33}$$

The term in brackets in the denominator of Equation 3-33 is the *sunhours*, the ratio of the annual average daily solar resource (kWh/m^2/day) to the standard rating insolation of 1 kW/m^2, which gives units of (hours/day), and I think of it as hours per day that the insolation level of the standard rating value is maintained in order to result in the same daily solar energy resource.

Hybrid PV/Battery/Generator Sizing

If a generator is part of an off-grid system, it may be less expensive to burn some generator fuel than to provide PV power on the shortest day of the year. The optimal value should be calculated to minimize life-cycle cost, and would require use of one of the optimization techniques described in Chapter 1 and probably a computer program such as HOMER. Depending on the cost of fuel at the site, the optimal size may be close to the sizing based on the annual average solar resource, so instead of dividing by $I_{\text{c,min,day}}$ in Equation 3-33, we would divide by $I_{\text{c,ave,day}}$, which is the average insolation over the course of the year in (kWh/m^2/day)

Grid-Tied PV System Sizing

The optimal size of a grid-tied PV system is often one of these thresholds:

No backfeed to utility: If power from the PV system may not exceed the load due to utility policy, or if the utility does not credit you for excess generation, then a good sizing strategy is to divide the average daytime load demand P_{load} (kW) by the balance-of-system efficiency. We call this P_{rated} because it is the rated output of the PV system at the 1 kW/m^2 standard rating condition.

$$P_{\text{rated}} = \frac{P_{\text{load}}}{\eta_{\text{bos}}} \tag{3-34}$$

Net metering: If utility policy is to carry a credit of energy (kWh) put back on the utility system for use up to 12 months later, then the sizing strategy is to divide the load (kWh/day) by the ratio of the annual average daily solar resource (kWh/m^2/day) to the standard rating insolation of 1,000W/m^2, which gives units of (kWh/day)/(hours/day), resulting in units of kW of solar power delivered to the load.

$$P_{\text{rated}} = \frac{E_{\text{load,day}}/\eta_{\text{bos}}}{\left[\dfrac{I_{C\text{ ave,day}}}{\left(1\dfrac{kW}{m^2}\right)}\right]} \tag{3-35}$$

Daily average solar insolation is greater in summer because the days are longer rather than because the instantaneous sun is more intense. A common sizing strategy is to meet the load on an average sunny summer day, which results in a smaller system but still one that exceeds the load during the day in order to offset the daily energy use in summer. In other seasons it uses more energy from the utility.

$$P_{\text{rating}} = \frac{E_{\text{load,day}}/\eta_{\text{bos}}}{\left[\dfrac{I_{C\text{ max,day}}}{\left(1\dfrac{kW}{m^2}\right)}\right]} \tag{3-36}$$

Annual Energy Savings

Electric energy generated by the PV array over any time period Δt may be estimated as the instantaneous power or average times the time period using the following equation:

$$E_{\text{solar}} = A_C I_{C,ave}\, \eta_{\text{solar}}\, \eta_{\text{bos}}\, \text{degr}\, (\Delta t) \tag{3-37}$$

For our simple hand calculation we have neglected the incident angle modifier K. For a single day, Δt would be one day and the energy delivered in the day would be

$$E_{\text{solar,day}} = A_C I_{\text{C,ave,day}}\, \eta_{\text{solar}}\, \eta_{\text{bos}}\, \text{degr} \tag{3-38}$$

The units on $I_{\text{C,ave}}$ and Δt have to be consistent. For example, if $I_{\text{C,ave}}$ was in units of kWh/m^2/day averaged over a month, then Δt would have to be in units of days per that month; or, as in the tables below, if $I_{C,\text{ave}}$ is in units of kWh/m^2/day averaged over the year, then Δt of would have to be in units of days per year.

It's tempting to simply multiply E_{solar} (kWh/year) by an average price of energy ($/kWh), but that only gives an accurate estimate of cost savings if the PV output is much less than the load.

A more general approach, which is much more accurate, is to calculate the utility bill, or generator operating costs, with and without the PV system. This is facilitated with a computer program that can mimic all the details of the load profile and the utility rate schedule. However, there is also a simple way to estimate it by hand. As we add to the collector area A_c of an array, we add kW of instantaneous P_{STC}, but we do not add hours per day that the sun is shining. So for a constant load we will start to sell power back to the utility during the day even as we need to buy it back at night.

For grid-tied systems sized based on the using all power on-site, all of this power may be credited at some retail value. For net-metered system where the utility absorbs excess power generation and gives it back later at no cost, all of this is credited at a retail value. Power generated in excess of the load without a net-metering policy is usually credited at a lower wholesale value, not credited at any value, or power may be prohibited from being injected into the utility system, in which case the excess power would have zero value.

The calculation of E_{solar} tells us how many kWh per day the PV system delivers, but not how many kW for which hours. To detail that delivery profile would require a computer simulation. However, a simple approximation comes rather close. First, we calculate P_{rated} and then calculate P_{STC} that would provide that P_{rated} after derating for temperature, balance of system efficiency and age degradation. STC assumes a very favorable 25°C cell temperature, and we must account for a higher cell temperature, which is more realistic. We assume for our simple hand calculation that the power level is constant over the day at this value.

And then we calculate the hours that the solar would deliver at this level in order to provide the calculated energy delivery E_{solar}:

$$\text{sunhours} = \frac{E_{\text{solar}}}{P_{\text{solar}}} \tag{3-39}$$

As illustrated in Figure 3-21, energy purchased from the utility without any solar is the "basecase"

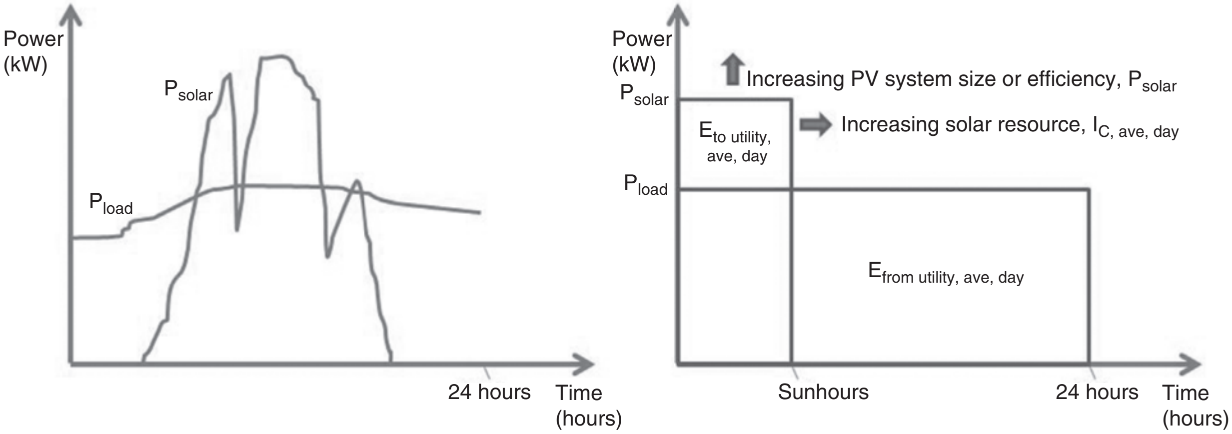

Figure 3-21. Varying load and solar power are considered constant in this simplified way of estimating power to and from the utility. As we add to the size of a PV system, we add to instantaneous power (kW), but we do not add time (hours) to the day that the PV generates power. Thus power is sold back to the utility well before the daily energy load (kWh) is met. (Figure by the author)

$$E_{\text{from utility,day,basecase}} = P_{\text{load}} * \left(24\,\frac{\text{hours}}{\text{day}}\right) \quad (3\text{-}40)$$

If the PV output is always less than the load, then there is no power sold back to the utility and power purchased from the utility in the PV case is simply

$$E_{\text{from utility,day,PV case}} = E_{\text{utility,day,basecase}} - E_{\text{solar,day}} \quad (3\text{-}41)$$

But if the PV output ever exceeds the load, then the amount of energy that still needs to be purchased from the utility when the sun is not shining is:

$$E_{\text{from utility,day,PV case}} = P_{\text{load}} * (24 \text{ hours} - \text{sunhours}) \quad (3\text{-}42)$$

And the amount of energy sold back to the utility as excess is:

$$E_{\text{to utility,day,PV case}} = (P_{\text{solar}} - P_{\text{load}}) * (\text{sunhours}) \quad (3\text{-}43)$$

These are the only two quantities that figure into the cost savings: (1) energy from utility, and (2) energy to utility. But we can also calculate the energy saved on-site by use of the PV as P_{solar}*sunhours. If these daily energy quantities are calculated using the monthly average values for P_{load} and sunhours, then they may be multiplied by the number of days per month to estimate monthly quantities. If they are calculated using P_{load} and sunhours averaged over the year, then they may be multiplied by 365 days per year to estimate annual energy quantities.

Capacity factor (CF) has two common definitions: (1) the fraction of rated output that a system provides continuously, or (2) the fraction of time that a system delivers its full rated capacity. In the approach described above we adopt the second definition:

$$CF = \frac{\text{sunhours}}{(24 \text{ hours})} \quad (3\text{-}44)$$

In the above description we consider a time period of one day, but the figure may be drawn for any time interval and is surprisingly accurate even with one year considered as the time period. At the other end of the time scale, if we consider the figure for very short time periods, such as one hour, then the fraction of the time that solar is not delivering is interpreted as the "reliability" of the system. In other words, there will be some hours, even during the day, when the PV cannot deliver its rated capacity due to weather. For example, using the definition of capacity factor offered in Equation 3-44, an hourly value of 500 kWh/h/m^2 taken from an hourly weather file is interpreted as 1,000 W/m^2 for 1/2 hour rather than 500 W/m^2 for the full hour. Both of these are approximate. The interpretation of 1,000 W/m^2 for 1/2 hour overestimates power sold back to the utility and the interpretation of 500 W/m^2 for 1 hour overestimates power saved on-site. As detailed in Chapter 1 already, reality is somewhere in between these two extremes, but the interpretation of 1,000W/m^2 for 1/2 hour is more conservative, since power sold back to the utility is usually of a lesser value than power saved on-site.

For an off-grid system there is no opportunity to sell excess power to any utility and power generated by the PV Array in excess of the load and in excess of the free battery capacity is wasted. In these cases, useful energy delivery of the PV system would be limited by the load being served over a single day.

$$E_{\text{solar,day}} \le E_{\text{load,day}} \quad (3\text{-}45)$$

Fuel energy savings will be greater than the electric delivery by the efficiency of the generator:

$$Q_{\text{Fuel savings}} = E_{\text{solar}}/\eta_{\text{generator}} \quad (3\text{-}46)$$

Where $Q_{\text{Fuel savings}}$ is annual fuel energy savings (kWh/yr) and $\eta_{\text{generator}}$ is the thermal efficiency of the fuel-fired electric generator.

Thus the three pieces of information that we need regarding the solar resource at a site are: $I_{\text{C, min day}}$, the minimum daily solar insolation for sizing off-grid systems; $I_{\text{C, max day}}$, the maximum daily solar insolation for sizing on-grid systems with no value for excess energy; and $I_{\text{C, ave day}}$, the average daily solar insolation for sizing net-metered systems and for estimating the annual energy delivery of either type. $I_{\text{C min day}}$ and $I_{\text{C max day}}$, are the two solar resource numbers listed in Table 3-12 for many US locations and Table 3-13 for many international locations. $I_{\text{C, ave day}}$ is listed in the solar resource tables (Table 4-19 for US locations and Table 4-20 for international locations) in Chapter 4.

ESTIMATING THE ENERGY COST SAVINGS OF A PHOTOVOLTAIC (SOLAR ELECTRIC) SYSTEM

Energy cost savings is estimated by first calculating the basecase utility bill without solar, then calculating the utility bill of the PV Case with solar, and taking the difference between the two cases. Annual energy cost savings may be estimated by multiplying each of the energy quantities (kWh/month or kWh/year) calculated above by a unit cost of energy ($/kWh). The annual cost of operating and maintaining the solar water heating system $C_{O\&M\,(\$/year)}$, is subtracted to estimate annual cost savings

$$\begin{aligned} C_{\text{savings}} = {} & (E_{\text{from utility,year,basecase}}\, C_{\text{elec retail}}) \\ & - (E_{\text{from utility,year,}PV_{\text{case}}}\, C_{\text{elec retail}}) \\ & + (E_{\text{to utility,year,}PV_{\text{case}}}\, C_{\text{elec,wholesale}}) - C_{\text{O\&M}} \end{aligned} \quad (3\text{-}47)$$

Where C_{savings} is annual cost savings ($/year); $c_{\text{elec, retail}}$ is the unit cost of electricity ($/kWh) representative of what the utility charges you for energy. This may be in addition to other charges on your bill such as peak demand, metering and billing and other adders that the solar system does not reduce the cost of. The

TABLE 3-12. MINIMUM DAILY AND MAXIMUM DAILY SOLAR RADIATION: GLOBAL INSOLATION ON T = HORIZONTAL SURFACE FOR FLAT-L COLLECTORS AND GLOBAL INSOLATION ON NORTH-SOUTH AXIS TRACKING AZIMUTH OF THE SUN FOR NONFOCUSING CCOLLECTORS FOR CITIES IN THE US, IN ORDER OF NAME OF STATE

		Global Tilt = Horizontal Flat Plate Collectors (kWh/m^2/day)		Global N-S Axis Non-focusing Collectors (kWh/m^2/day				Global Tilt = Horizontal Flat Plate Collectors (kWh/m^2/day)		Global N-S Axis Non-focusing Collectors (kWh/m^2/day				Global Tilt = Horizontal Flat Plate Collectors (kWh/m^2/day)		Global N-S Axis Non-focusing Collectors (kWh/m^2/day	
State	**City**	$I_{C,max}$	$I_{C,min}$	$I_{C,max}$	$I_{C,min}$	**State**	**City**	$I_{C,max}$	$I_{C,min}$	$I_{C,max}$	$I_{C,min}$	**State**	**City**	$I_{C,max}$	$I_{C,ave}$	$I_{C,max\ x}$	$I_{C,min}$
Alabama	Huntsville	5.7	3.3	8.0	2.9	Florida	Tampa	6.3	4.4	8.3	4.2	New York	Buffalo	501			
Alaska	Anchorage	4.6	0.6	6.3	0.3		Orlando	5.8	3.9	8.0	3.8		New York	5.6	4.6	4.1	2.9
	Juneau	4.5	.81	6.8	0.4		Key West	6.4	4.7	7.5	4.8	North Carolina	Charlotte	5.7	3.6	7.9	3.2
Arizona	Chandler	6.9	4.7	10.5	4,4		Fort Lauderdale	5.9	4.1	8.1	4.1		Raleigh	5.7	3.6	7.9	3.1
	Flagstaff	6.7	4.8	10.1	4.4	Georgia	Atlanta	5.8	3.7	8.0	3.3		Greensboro	5.6	3.6	7.9	3.1
	Mesa	6.7	4.9	10.6	4.5	Hawaii	Hilo Honolulu	5.2 6.2	4.3 4.8	6.5 8.7	4.5 5.1	North Dakota	Fargo	6.0	2.7	8.9	1.9
	Phoenix	7.5	4.9	11.4	4.4	Idaho	Boise	7.0	2.6	10.9	2.0	Ohio	Columbus	5.4	2.2	7.6	1.8
	Scottsdale	7.0	4.6	10.7	4.3	Illinois	Aurora	5.3	2.0	7.3	1.7	Oklahoma	Oklahoma City	6.3	4.1	9.3	3.6
	Tucson	7.3	5.1	11.2	4.8		Joliet	5.5	2.5	7.6	2.1	Oregon	Portland	5.8	1.6	8.3	1.2
California	Bakersfield	7.3	3.2	11.1	2.7		Chicago	5.7	2.4	8.0	1.9		Salem	6.1	1.6	8.9	1.3
	Chula Vista	6.6	4.3	9.3	4.2	Indiana	Fort Wayne	5.6	2.2	7.9	1.8	Pennsylvania	Philadelphia	5.5	2.9	7.7	2.4
	Fresno	7.3	2.8	11.2	2.4	Kansas	Overland Park	5.8	3.4	8.1	3.0	Rhode Island	Providence	5.5	2.9	7.5	2.2
	Inyokern	7.2	4.7	11.2	4.4		Wichita	6.3	3.8	9.1	3.2	South Carolina	Columbia	5.9	3.8	7.8	3.4
	Lancaster	7.1	4.4	10.9	4.1	Kentucky	Lexington-Fayette	5.6	2.7	7.8	2.3	South Dakota	Sioux Falls	6.1	3.0	8.9	2.3
	Long Beach	6.7	4.2	9.3	3.7	Lousiana	Shreveport	6.0	3.7	8.2	3.4	Tennessee	Memphis	6.0	3.4	8.5	3.0
	Modesto	7.0	2.2	10.5	2.0		New Orleans	5.7	3.7	7.7	3.5	Texas	Amarillo	6.4	4.6	9.5	4.1

	Ontario	6.2	3.9	8.7	3.7	Maine	Bangor	5.0	2.3	6.9	1.7		Arlington	6.2	3.8	8.8	3.6
	Oxnard	6.1	4.2	8.4	4.0	Maryland	Baltimore	5.6	3.1	7.8	2.5		Brownsville	5.9	3.6	8.3	3.5
	Palmdale	7.1	4.5	11.0	4.2	Massacheusettes	Boston	5.6	2.9	7.7	2.2		Dallas/Fort Worth	6.4	4.1	9.2	3.8
	Riverside	6.3	4.1	8.8	3.8	Michigan	Houghton	5.6	1.8	8.1	1.4		El Paso	7.3	5.1	10.8	4.8
	Sacramento	7.2	2.7	11.1	2.2		Detroit	5.6	2.1	8.0	1.7		Houston	5.5	3.5	7.6	3.3
	San Diego	6.5	4.6	8.8	4.2	Minnesota	Duluth	5.6	2.5	8.1	1.9		Laredo	6.2	3.6	8.8	3.5
	San Francisco	6.8	3.4	9.7	2.8	Mississippi	Natchez	5.4	3.5	7.3	3.3		Lubbock	6.3	4.6	9.4	4.2
	Santa Rosa	6.9	3.5	10.3	3.2	Montana	Billings	6.5	3.1	9.8	2.2		San Antonio	6.3	4.1	8.7	3.9
	Stockton	6.9	2.4	10.5	2.1		Kalispell	6.2	1.7	9.5	1.3	Utah	Salt Lake City	6.7	2.9	10.1	2.3
	Truckee	6.9	3.2	10.3	2.8	Missouri	St. Louis	5.9	3.1	8.3	2.5		Provo	6.9	3.1	10.2	2.7
Colorado	Eagle	6.4	3.9	9.9	3.2	Nebraska	Omaha	6.0	3.2	8.7	2.5	Vermont	Burlington	5.6	2.1	7.9	1.7
	Alamosa	6.8	5.2	10.8	4.5		Lincoln	5.7	2.9	7.9	2.5	Virginia	Richmond	5.6	3.3	7.9	2.8
	Denver	6.1	4.2	9.1	3.3	Nevada	Las Vegas	7.4	4.9	11.6	4.2		Chesapeake	5.6	3.6	7.8	3.2
	Fort Collins	6.3	4.2	9.2	3.7		Reno	7.1	3.9	11.1	3.2		Norfolk	5.6	3.4	7.7	2.9
	La Junta	6.6	4.0	9.8	3.7	New Hampshire	Concord	5.6	2.8	7.9	2.2	Washington	Yakima	6.7	2.2	10.3	1.6
Connecticut	Hartford	5.4	2.7	7.3	2.1	New Jersey	Newwark	5.4	2.8	7.4	2.2	Washington	Seattle	5.7	1.4	8.0	1.0
Delaware	Wilmington	5.6	3.0	7.8	2.5	New Mexico	Albuquerque	7.2	5.0	10.9	4.5	West Virginia	Huntington	5.4	2.5	7.5	2.1
Florida	Jacksonville	6.0	3.9	7.8	3.7		Las Cruces	7.1	4.8	10.2	4.6	Wisconsin	Madison	5.8	2.6	8.1	2.0
	Miami	6.1	4.5	7.0	4.5	New York	Albany	5.5	2.4	7.7	1.9	Wyoming	Cheyenne	6.1	3.9	9.1	3.1
													Dubois	6.2	3.7	8.9	2.8

Sources: (NASA LARC 2012) (Marion & Wilcox, 1994).

TABLE 3-13. MINIMUM DAILY AND MAXIMUM DAILY SOLAR RADIATION: GLOBAL INSOLATION ON TILT = HORIZONTAL SURFACE FOR FLAT PLATE COLLECTORS AND GLOBAL INSOLATION ON NORTH-SOUTH AXIS TRACKING AZIMUTH OF THE SUN FOR NON-FOCUSING COLLECTORS FOR CITIES IN VARIOUS COUNTRIES, IN ORDER OF NAME OF THE COUNTRY

		Global Tilt = Horizontal Flat Plate Collectors (kWh/m^2/day)		Global N-S Axis Nonfocusing Collectors (kWh/m^2/day)				Global Tilt = Horizontal Flat Plate Collectors (kWh/m^2/day)		Global N-S Axis Nonfocusing Collectors (kWh/m^2/day				Global Tilt = Horizontal Flat Plate Collectors (kWh/m^2/day)		Global N-S Axis Nonfocusing Collectors (kWh/m^2/day	
Country	**City**	$I_{C,\max}$	$I_{C,\min}$	$I_{C,\max}$	$I_{C,\min}$	**Country**	**City**	$I_{C,\max}$	$I_{C,\min}$	$I_{C,\max}$	$I_{C,\min}$	**Country**	**City**	$I_{C,\max}$	$I_{C,\min}$	$I_{C,\max}$	$I_{C,\min}$
Afghanistan	Kabul	7.0	4.5	10.7	4.2	Congo	Kinshasa	4.9	3.3	5.7	3.6	Korea, S.	Seoul	4.4	2.6	5.5	2.3
Albania	Tirana	6.9	2.7	10.4	2.3		Lubumbashi	7.0	4.7	8.9	5.6	Korea, S.	Suwon	5.5	3.8	6.8	3.8
Algeria	Algiers	7.3	5.5	11.0	5.5	Cook Islands	Pukapuka	6.2	5.2	7.8	6.2	Kuwait	Kuwait City	6.9	4.0	10.5	3.9
Angola	Luanda	5.7	3.7	7.0	5.8	Costa Rica	San José	6.3	4.4	7.9	5.2	Kyrgyzstan	Osh	6.7	3.4	9.8	2.9
Argentina	Buenos Aires	6.4	3.4	9.0	3.2	Côte d'Ivoire	Abidjan	5.4	3.9	6.5	4.3.	Latvia	Riga	4.6	0.8	6.7	0.4
	Mendoza	6.6	3.7	9.6	3.4	Cuba	Havana	6.3	4.8	8.1	5.3	Lebanon	Beirut	6.2	3.1	9.2	2.9
	Ushuaia	4.7	1.0	6.7	0.7	Czech Republic	Prague	4.5	1.5	6.0	1.0	Macedonia	Skopje	6.0	2.0	8.7	1.6
Australia	Adelaide	6.2	3.7	8.7	3.4	Denmark	Copenhagen	4.8	0.9	7.4	0.5	Madagascar	Antananarivo	5.6	4.0	6.0	4.2
	Alice Springs	6.9	5.4	10.1	5.6	Egypt	Cairo	6.7	4.1	10.0	4.0	Malasia	Kuala Lumpur	5.0	4.1	5.7	4.7
	Canberra	6.6	3.4	9.6	3.2	England	Leeds	4.1	1.4	5.5	0.8	Mali	Bamako	6.5	5.0	8.1	5.9
Austria	Vienna	4.9	1.8	6.6	1.3		London	4.1	1.1	5.7	0.7	Mexico	Chihuahua	6.9	5.6	9.7	5.6
Azerbaijan	Baku	5.5	2.8	7.7	2.4	Ethiopia	Addis Ababa	5.9	3.7	7.2	4.1		Merida	6.2	4.9	8.0	5.2
Bahamas	Nassau	6.6	4.7	9.2	4.8	Finland	Helsinki	5.1	0.8	8.1	0.4		Mexico City	6.3	4.6	7.8	5.4
Bangladesh	Chittagong	5.8	4.0	7.0	4.5	France	Marseille	6.4	2.9	9.7	2.2		Monterey	6.2	4.9	8.0	5.0
	Dhaka	6.0	3.9	7.3	4.6		Paris	5.0	1.1	7.2	0.8	Mongolia	Ulan Bator	6.0	3.3	7.6	2.3
Belarus	Minsk	4.6	1.0	6.5	0.7		Lyon	5.7	1.3	8.5	0.9	Morocco	Casablanca	5.8	3.4	8.1	3.5
Belgium	Antwerp	4.6	1.3	6.3	0.9	Georgia	Tbilisi	5.5	2.0	7.8	1.7	Mozambique	Maputo	6.2	5.2	8.6	5.3

Belize	San Ignacio	6.1	4.3	7.7	4.6	Germany	Frankfurt	4.4	1.3	6.2	0.9	Myanmar	Mandalay	6.5	4.4	8.1	5.1
Bhutan	Thimpu	5.6	4.5	6.7	5.4		Hamburg	4.5	1.0	6.2	0.7		Yangon	6.5	3.2	8.2	3.4
Bolivia	Santa Cruz	5.6	3.4	7.0	3.5		Munich	4.7	1.7	6.7	1.2	Nepal	Kathmandu	6.9	4.4	8.8	5.6
Bosnia	Sarajevo	5.3	1.6	7.3	1.3	Iceland	Reykjavik	4.1	0.7	4.6	0.1	Netherlands	Amsterdam	5.2	1.2	7.4	0.8
Brazil	Rio de Janeiro	5.2	4.4	6.4	4.5	India	Ahmadabad Gujarat	7.0	4.2	9.7	4.9	New Zealand	Auckland	6.0	2.9	8.3	2.6
	Brasília	5.6	4.4	6.9	5.1		Bangalore	7.1	4.0	9.2	4.6	Nicaragua	Managua	6.9	5.4	8.8	6.5
Canada	Edmonton	5.6	2.8	8.3	1.7		Bhopal	6.6	3.6	8.4	4.0	Nigeria	Lagos	5.6	3.9	6.9	4.4
	Montreal	4.9	2.1	7.6	1.6		Calcutta	5.8	4.2	7.4	4.7	Norway	Oslo	5.0	1.0	7.4	0.5
	Saskatoon	5.7	3.5	9.0	2.3		Chandigarh	6.9	5.2	10.0	5.1	Pakistan	Faisalabad	5.9	4.8	8.7	4.6
	Toronto	5.5	1.7	7.8	1.3		Delhi	6.8	4.8	9.2	5.1		Gujranwala	6.7	4.7	9.9	4.6
	Vancouver	5.8	1.2	8.4	0.9		Dhera Dun Uttaranchal	6.8	4.7	10.0	5.4		Hyderabad	6.3	4.5	9.0	4.5
	Winnipeg	5.7	2.8	8.6	2.0		Gauhati Assam	6.2	3.8	7.5	4.7		Karachi	6.1	4.9	8.4	5.5
	Yellowknife	5.5	1.2	9.1	0.4		Goa	6.8	3.8	8.6	4.4		Lahore	5.8	3.9	8.0	3.8
Chile	Punta Arenas	5.1	1.4	7.3	0.9		Hyderabad	6.6	3.7	8.3	4.2		Multan	6.0	4.5	8.2	4.4
	Santiago	5.9	1.6	8.3	1.5		Itanagar Arunchal	4.9	3.9	5.3	4.3		Peshawar	6.5	4.7	9.5	4.5
China	Baotou Neimongol	6.3	4.9	8.5	4.3		Kargil Kashmir	6.2	4.1	8.6	3.9		Quetta	6.8	4.8	10.2	4.8
	Beihai Guangxi	4.6	3.1	5.9	3.2		Leh Ladakh	6.5	4.4	8.8	4.3	Paraguay	Asunción	5.8	3.9	7.9	3.9
	Beijing	5.0	3.3	6.8	2.8		Lucknow Uttar	6.3	4.3	8.5	5.0	Peru	Lima	7.1	3.4	9.2	3.8
	Changsha Hunan	4.6	1.8	6.0	1.8		Ludhiana Punjab	6.6	5.1	8.6	5.0	Philippines	Davao	5.6	4.6	7.0	5.3
	Chengdu Sichuan	3.4	1.5	3.9	1.4		Madras	6.8	4.4	8.6	5.1	Poland	Warsaw	4.7	1.0	6.7	0.7

(continued)

TABLE 3-13. ***(Continued)***

		Global Tilt = Horizontal Flat Plate Collectors (kWh/m^2/day)		Global N-S Axis Nonfocusing Collectors (kWh/m^2/day)				Global Tilt = Horizontal Flat Plate Collectors (kWh/m^2/day)		Global N-S Axis Nonfocusing Collectors (kWh/m^2/day				Global Tilt = Horizontal Flat Plate Collectors (kWh/m^2/day)		Global N-S Axis Nonfocusing Collectors (kWh/m^2/day	
Country	**City**	$I_{C,\max}$	$I_{C,\min}$	$I_{C,\max}$	$I_{C,\min}$	**Country**	**City**	$I_{C,\max}$	$I_{C,\min}$	$I_{C,\max}$	$I_{C,\min}$	**Country**	**City**	$I_{C,\max}$	$I_{C,\min}$	$I_{C,\max}$	$I_{C,\min}$
China *(continued)*	Chungking	3.6	1.2	4.3	1.2	India *(continued)*	Manali Himachal	5.9	3.8	7.9	3.8	Russia	Grozny Chechnya	5.3	2.5	7.8	1.9
	Fuzhou Fujian	4.9	2.0	6.4	2.1		Mumbai	6.8	3.4	8.6	3.8		Moscow	4.9	1.0	7.4	0.5
	Guangdong Tianjin	5.9	4.6	7.9	4.2		Patna Bihar	6.9	4.2	9.1	5.2	Saudi Arabia	Jidda	6.8	5.2	9.6	5.5
	Ganzhou Jiangxi	4.9	2.5	6.4	2.5		Pune	6.9	4.2	9.0	4.9	Scotland	Edinburgh	4.2	1.4	5.9	0.7
	Guiyang, Guizhou	3.9	1.6	4.5	1.6		Shrinagar Kashmir	6.4	2.8	9.4	2.6	Senegal	Dakar	6.8	5.1	8.9	6.1
	Haikou Hainan	5.1	3.7	6.8	3.7		Trivandrum	6.4	4.7	8.2	5.7	Somalia	Mogadishu	7.2	5.6	9.5	7.2
	Harbin Heilongjiang	5.0	2.8	7.3	2.1	Indonesia	Jakarta	4.4	3.6	5.1	4.0	South Africa	Cape Town	6.9	3.8	10.2	4.2
	Hefei Anhui	4.7	2.8	5.5	2.6		Palembang	5.0	4.2	6.0	4.8		Pretoria	6.6	5.8	8.6	6.0
	Hong Kong	4.9	3.2	6.4	3.4	Iran	Shiraz	6.7	4.8	9.9	4.5	Spain	Barcelona	6.2	3.3	9.0	2.8
	Jilin Jilin	5.8	4.2	7.3	3.2		Tabriz	6.8	3.2	10.1	2.9		Seville	6.6	3.6	9.8	3.2
	Jinzhou Liaoning	5.7	3.4	8.4	3.1		Tehran	6.8	3.6	10.0	3.3	Sweden	Linkoping	5.0	1.3	7.4	0.6
	Kunming Yunan	5.5	3.5	6.9	3.8	Iraq	Baghdad	6.4	4.2	9.4	3.9	Switzerland	Geneva	5.3	1.3	7.8	1.0
	Lanzhou Gansu	5.0	2.9	6.9	2.6		Mosul	5.6	2.7	7.8	2.4	Syria	Aleppo	6.8	3.1	10.6	2.8

	Lhasa Tibet	6.9	5.5	10.5	5.5	Ireland	Dublin	4.2	1.1	5.9	0.7	Taiwan	Taipei	4.6	2.5	5.5	2.4
	Tsingtao Shandong	3.8	2.9	4.5	2.6	Israel	Haifa	6.8	3.7	10.3	3.5	Tajikistan	Dushanbe	6.7	3.2	9.8	2.8
	Shanghai	4.4	2.6	5.6	2.4	Italy	Milan	5.6	2.6	8.3	1.9	Tanzania	Dar es Salaam	5.5	3.9	6.9	4.4
	Shenzhen Guangdong	4.6	3.2	5.9	3.4		Palermo	7.1	3.2	10.7	2.8	Thailand	Bankok	5.7	4.3	6.9	4.9
	Shijiazhuang Hebei	5.9	4.4	7.4	4.3		Venice	5.3	1.6	7.7	1.2	Tunisia	Sidi Bou Said	6.6	3.3	9.8	3.0
	Suzhou Jiangsu	4.6	3.7	6.0	3.6	Japan	Akita	4.6	1.6	5.8	1.3	Turkey	Antlalya	6.4	2.9	9.4	2.6
	Urumqi Xinjiang	5.7	2.2	8.5	1.7		Nagasaki	5.6	3.0	7.4	2.8		Bursa	6.1	2.2	8.8	1.9
	Wuhan Hubei	4.4	2.2	5.6	2.1		Sapporo	4.6	2.4	6.3	1.9		Istanbul	6.6	1.9	9.8	1.6
	Xian Shaanxi	4.4	2.4	5.1	2.2		Tokyo	3.7	2.6	4.4	2.6	Uganda	Kampala	5.5	4.6	6.7	5.5
	Xining Qinghai	5.8	3.7	7.8	3.9		Yamagata	4.6	2.2	6.0	1.9	Ukraine	Odessa	5.5	1.3	8.2	1.0
	Yanchi Ningxia	5.9	4.7	7.6	5.7	Kazakhstan	Karaganda	5.7	2.5	8.8	1.8	Venezuela	Caracas	5.0	4.1	5.9	4.6
	Zhengzhou Henan	6.6q	3.3	6.4	2.6	Kenya	Nairobi	6.1	3.8	7.7	4.3	Virgin Islands	Charlotte Amalie	7.0	5.5	9.1	5.9
Colombia	Bogota	5.2	3.6	6.2	4.0	Korea, N.	Pyongyang	5.0	3.2	6.7	2.8	Yemen	Sana'a	5.3	4.3	6.7	4.7

Sources: (NASA LARC 2012).

price $c_{\text{elec wholesale}}$ is the price of electricity (also in \$/kWh) that the utility pays you for energy put back on the utility system. This is representative of what the utility saves as a result of your PV system delivery, and is often called the *avoided cost*, *buy-back rate*, or *feed in tariff*.

Life Cycle Cost Analysis of Photovoltaic (Solar Electric) System

A simple economic model is adequate to evaluate life cycle cost of a PV system. The life cycle cost, LCC, of the basecase is the annual utility bill times a present worth factor. The LCC of the PV Case is the initial cost of implementing the PV system plus the same present worth factor times the utility bill (as reduced by the PV delivery) and the increased operation and maintenance costs associated with the PV system.

The difference between LCC_{Basecase} and LCC_{PVCase} is the net present value of the life cycle savings, LCS, of a project; and is approximated by

$$LCS = (C_{\text{savings}})\ PWF\ (d,\ N) - C_{\text{initial}} \tag{3-48}$$

Where the present worth factor, PWF(d,N), is the factor to discount at the rate of d percent per year a stream of N annual cash flows down to their present value. For example, the PWF for $N = 25$ years of cash flows at $d = 3$ percent discount rate is 17.4 years. The PWF has units of years, but it reflects that the value of \$1/year for 25 years is worth only \$17.4 today.

Another useful metric is the savings to investment ratio, or SIR, which is the ratio of life cycle savings to the investment.

$$SIR = \frac{C_{\text{savings}} PWF(d,N)}{C_{\text{intial}}} \tag{3-49}$$

An SIR of greater than one (SIR > 1) indicates that a project is cost effective. The size of the PV system, initial cost, annual energy delivery, annual cost savings, and payback period may be estimated by this simple hand calculation, but subsequently more detailed analysis using computer tools must be used to refine the estimate of economic savings.

Example Calculations for Size, Cost, and Electricity Delivery of Photovoltaics (Solar Electric) System

In this example (Table 3-14), we consider a photovoltaic system for a small single-story commercial building in Honolulu, Hawaii of 1,000 m^2 (10,000 sf) floor area. With expensive petroleum as the island's major source of power, the average commercial electric rate in Hawaii is \$0.34/kWh (EIA 2012). In order to espouse an environmental ethic, the building owner wishes to advertise that the building produces as much electricity as it consumes over the course of a year. Estimate the size (both kW and m^2) and the cost of a system to meet that goal. Will the solar collectors fit on the roof of the building? Estimate monthly average daily energy delivery in summer, when the solar resource is a maximum, and also in winter, when it is a minimum. Estimate life-cycle cost effectiveness of the system.

TABLE 3-14. EXAMPLE CALCULATIONS OF THE SIZE (kW), COST (\$), ANNUAL ENERGY DELIVERY (kWh/YEAR), AND COST-EFFECTIVENESS OF A PHOTOVOLTAIC SYSTEM

Electric utility (load) information		
$E_{\text{load,year}}$	Annual electric energy consumption of building (10,000 sf)*(11 kWh/sf/year)	110,000 kWh/year
P_{load}	Building electric demand	12.6 kW
c_{retail}	price of electricity from utility	\$0.34 \$/kWh
$c_{\text{wholesale}}$	value of electricity to utility	\$0.19 \$/kWh
Stipulated design values		
η_{STC}	STC efficiency of PV modules	0.17
Δ	Temperature coefficient of power	0.0044 1/C
NOCT	Nominal operating cell Temperature	47 C
η_{bos}	Efficiency of balance-of-system	0.77
degr	Degradation due to age	0.94
Solar resouce from map or table		
$I_{C,\text{max day}}$	Maximum daily solar insolation on tilt = latitude (Table 3-12)	7.3 kWh/m^2/day
$I_{C,\text{ave day}}$	Average daily solar insolation on tilt = latitude (Table 4-19)	5.7 kWh/m^2/day
$I_{C,\text{min day}}$	Minimum daily solar insolation on tilt = latitude (Table 3-12)	2.8 kWh/m^2/day
T_{ambient}	Annual average ambient temperature	17.4 C

Calculated energy results

$E_{\text{load,day}}$	Daily energy requirement $E_{\text{load,year}}/(365 \text{ days/year})$	301 kWh/day
P_{solar}	Solar power required to meet daily energy load (Equation 3-35)	52.9 kW_{PTC}
P_{STC}	Rated power STC corresponding to $P_{\text{solar}} = P_{\text{solar}}/(((\eta_{\text{bos}}\text{degr}))^* (1 - \delta^*((T_{\text{ambient}} + ((\text{NOCT} - 20))/((800))^*1000) - 25)))$	82.5 kW_{STC}
A_{c}	Surface area of solar collector positioned at tilt = latitude (Equation 3-32)	485.6 m^2
$E_{\text{solar,day,max}}$	Maximum daily solar energy delivery equation $P_{\text{solar}}{}^* I_{c,\text{max,day}}/(1\text{kW/m}^2)$ (Equation 3-38)	386 kWh/day
$E_{\text{solar,day,ave}}$	Annual average daily solar energy delivery $P_{\text{solar}}{}^* I_{c,\text{ave,day}}/(1\text{kW/m}^2)$ Equation 3-38	301 kWh/day
$E_{\text{solar,day,max}}$	Minimum daily solar energy delivery equation $P_{\text{solar}}{}^* I_{c,\text{min,day}}/(1\text{kW/m}^2)$ (Equation 3-38)	148 kWh/day
Annual average sunhours	Annual average sunhours $I_{c,\text{ave}}/(1\text{kW/m}^2)$ (Equation 3-39)	5.7 sunhours/day
$E_{\text{from utility,PV case}}$	Energy from utility with PV, $P_{\text{load}}{}^*(24\text{-sunhours})^*(365 \text{ days/year})$ (Equation 3-42)	83,875 kWh/year
$E_{\text{to utility, PV case}}$	Energy to utility with PV, $(P_{\text{solar}}\text{-}P_{\text{load}})^*\text{sunshours}^*(365\text{days/year})$ (Equation 3-43)	83,875 kWh/year
	PV energy used on-site	26,125 kWh/year
E_{solar}	Total annual PV energy delivery $\text{Psolar}^* I_{C,\text{ave,day}}/(1\text{kW/m}^2)^* (365 \text{ days/year})$	109,990 kWh/year

Economic results

C_{savings}	Annual utility energy cost savings (Equation 3-47)	\$24,795/year
C_{initial}	Initial cost of PV system, $P_{\text{STC}}{}^*\$4.61/\text{watt}$	\$380,534
$C_{\text{O\&M}}$	Annual operation and maintenance cost $C_{\text{initial}}{}^*0.35\%/\text{year}$	\$1,332/year
LCS	Life cycle savings $(C_{\text{savings}} - C_{\text{O\&M}})^*\text{PWF} - C_{\text{initial}}$ (Equation 3-48)	\$27,724
SPB	Simple pay-back period $C_{\text{initial}}/(C_{\text{savings}} - C_{\text{O\&M}})$	16.22 Years
SIR	Savings-to-investment ratio $(C_{\text{savings}} - C_{\text{O\&M}})^*\text{PWF}/C_{\text{initial}}$ (Equation 3-49)	1.07
LCOE	Levelized cost of solar energy, equation $(C_{\text{initial}}/\text{PWF}+C_{\text{O\&M}})/E_{\text{solar}}$	\$0.21/kWh

Annual energy consumption is reported to be 110,000 kWh/year. Say this building is operating at this level for 24 hours a day and 7 days a week, such as an all-night convenience store might, so the average load is 12.6 kW. The average daily load is 301 kWh/day.

The value credited by the utility for surplus PV energy provided back to the utility is \$0.189/kWh (DSIRE 2011). Assuming a 3 percent discount rate and a 25-year analysis period, the present-worth factor is 17.4 years.

Referring to Table 3-12 of solar resource data, we find Honolulu, Hawaii, and the value of $I_{c,\text{max}}$ is 6.2 and the value of $I_{C,\text{min}}$ is 4.8 $\text{kWh/m}^2\text{/day}$ (NASA LARC 2012; Marion and Wilcox, 1994). Also from Table 4-19 in Chapter 4 or from the climate references, we find that the average solar resource in Honolulu is 5.7 $\text{kWh/m}^2\text{/day}$.

In this example we neglect the effect of the incident angle modifier, *K*, which would be taken into account in a computer simulation. Also, we calculate efficiency loss due to temperature using the annual average temperature, which would be more accurate to estimate hourly with computer simulation.

We find that under the set of assumptions in this example, a photovoltaic system for this building could offset 100 percent of the annual electric requirements with a 82.5 kW_{STC} system that would occupy 486 m^2 (5,225 sf) of the 1,000 m^2 roof. The basecase utility bill of $37,653/year is replaced by the PV case utility bill that consists of $28,710 paid for conventional energy minus a credit of $15,852 for power put back on the utility system for a net annual utility savings of $24,795/year. The simple payback period is 16 years and the savings-to-investment ratio is 1.07. Since the present value of the life-cycle savings exceed the investment (SIR > 1), we deem the project considered in this example to be cost-effective. If we amortize the initial cost over 25 years, we can calculate the levelized cost of energy associated with the solar at $0.21/kWh. Since this building injects an amount of energy into the utility system that equals its withdraw of energy from the utility, it may claim the moniker “net-zero building.”

COMPUTER TOOLS FOR ANALYSIS OF PHOTOVOLTAIC SYSTEMS

The power output of the PV system varies with insolation and temperature that change over time. In off-grid systems, the state-of-charge of the battery depends on the previous hour’s solar resource and load. Thus, the simple hand calculations we have explained above should be considered approximate, and a computer time-series simulation is a much more accurate way to model the details of the load and conditions. Usually, a one-hour time step is used, although 15-minute time step matches most utility billing calculations. Engineers use other computer programs (ETAP) to model the transient details of electrical power systems that occur on shorter time scales.

Most computer programs are “efficiency-based models” that multiply the solar power resource (kW) by an efficiency to calculate the power out (kW). One program, WATSUN-PV, calculates the voltage and current independently, which is very useful for battery performance models. Most of the computer programs model efficiency or power output of the PV as a function of temperature and model the inverter efficiency as a function of percent load. For off-grid systems, most programs include the temperature dependence and charging/discharging characteristics of the battery. WATSUN-PV has the most detailed battery model, but it is not possible to find all the information to inform this model from the battery manufacturers. Computer programs calculate the power delivery at each time interval, and the state of charge of the battery at the end of the previous time interval becomes the starting condition for the next time interval in a time series simulation. PVFORM was an early simulation from Sandia National Laboratory, and while it is not listed here, I recognize it as the grand–daddy of most of the programs below.

There are perhaps 100 computer tools for the design and evaluation of PV systems—all the way from manufacturing to performance measurement and reporting. A comparison of some few computer simulation programs is provided based on review of on-line tools directories (DOE OBT 2011), interviews with practioners, and funding agencies, and involvement or experience of the author. This comparison (Table 3-15) is certainly not inclusive of all programs available and is not intended to indicate that one is any better than another; rather, that each has appropriate applications. Where possible I’ve used the developers own description of their tool. The programs are compared according to the following criteria:

- Nonproprietary: computer program is available to competing commercial interests.
- Calculations may be checked: calculations which are used to generate the results are visible in a spreadsheet form or well-described in program documentation.
- Climate data: extensive weather data for multiple countries or access to climate data is facilitated.
- Well tested: computer program used on many projects to vet bugs and ensure usefulness and confidence in the results.
- Cost: free or low cost.

TABLE 3-15. COMPARISON OF COMPUTER SOFTWARE TOOLS FOR DESIGN AND ANALYSIS OF PV SYSTEMS PERFORMANCE

	Nonproprietary	Visible or well-described calculations	Extensive weather data	Well tested	Free or Low cost	User support	Recently updated	Documentation
3Tier			*	*		*	*	*
FRESA	*		*		*			*
Polysun			*	*		*	*	*
PV*SOL			*	*		*	*	*
PVSYST			*	*		*	*	*
PVWatts	*		*	*	*		*	*
REO	*	*					*	*
RETScreen	*	*	*	*	*	*	*	*
Solar Design Tool			*	*		*	*	*
Solar-Estimate.org				*	*	*	*	
Solar GIS pvPlanner			*	*		*	*	*
Sol-Opt	*			*	*	*	*	*
Solmetric iPV			*	*				
System Advisor Model (SAM)	*	*		*	*	*	*	*
TRNSYS		*		*		*	*	*

- User support: contact information is valid and support and training are available.
- Recently updated: program is reflective of current models and computer systems.
- Documentation: complete reference material is available.

A short description is provided for each tool along with other information, including expertise required, users, audience, input, output, computer platforms, programming language, strengths, weaknesses, technical contact, and availability.

3TIER

3TIER is based on delivering information from a very high resolution resource dataset of processed satellite information. There are several products offered for prospecting for projects or detailed resource data analysis. The FirstLook product is very popular. Focus is on high resolution (both spatially and time-series) data, rather than system energy or economic models.

- Expertise required: No special training required.
- Users: unknown but a lot, the FirstLook website is very popular.
- Audience: Project prospectors; feasibility studies; due diligence.
- Input: Identify your location using on-line interface.
- Output: Up to 10 years historical data for the location; 3-km resolution; maps; data layer for GIS programs.
- Computer platform: On-line Internet application.
- Strengths: good source of solar resource data for a site.
- Weaknesses: No economic models, just resource data.
- Contact: Telephone: 206-325-1573; Website: 3tier.com/en/contact.
- Cost: $5000/year license fee.

FRESA

FRESA is used to identify and prioritize renewable project opportunities for subsequent feasibility study. The photovoltaics module is based on average solar resource data (kWh/m^2/day, sunhours/day) similar to our simple hand calculation above. Lifecycle cost calculations comply with 10 CFR 436.

- Expertise required: Must be able to gather summary information on building and installation energy use patterns; intended for use by trained auditors; results should be interpreted by someone familiar with the limitations of the program.
- Users: 50 contractors under the SAVEnergy Audit Program administered by US Department of Energy's Federal Energy Management Program.
- Audience: Building energy auditors.
- Input: Summary energy load data; solar and wind resource data provided in a database indexed by ZIP code;
- Output: Annual cost and energy savings; life cycle economics; an early indicator if an option is viable; viable options ranked by savings-to-investment ratio.
- Computer platform: PC-compatible, web-based application.
- Programming language: Web-based application.
- Strengths: Establishes consistent methodology and reporting format for a large number of audits in varying locations and with varying building use types; sophisticated analyses of technology performance and cost while keeping data requirements to a minimum.
- Weaknesses: Provides only first-order screening, to focus design; requires more detailed feasibility analyses on applications most likely to be cost-effective; requires high level of knowledge about energy audits and the limitations of the program; does not model details of utility rate schedule.
- Contact: Dan Olis; National Renewable Energy Laboratory; dan.olis@nrel.gov; National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401 United States;
- Website: https://www3.eere.energy.gov/femp/fresa/ Cost: Free.

HOMER

HOMER stands for Hybrid Optimization Multiple Energy Resources. It combines many resources to meet a load profile in an hourly simulation. Can model grid-tied PV systems and complicated off-grid systems involving batteries and other types of generators.

- Expertise required: One-day training recommended.
- Users: Over 60,000.
- Audience: Engineers, researchers, educators.
- Input: Hourly and daily load profile for each month; requires detailed input to configure systems and describe characteristics of components. Utility to easily import climate data.
- Output: efficiency, load and fraction of load met by solar; equipment cost; life cycle cost. Rank-orders different configurations in order of life cycle cost. Details of fuel consumption and run-time for off-grid generators.
- Computer platform: Windows 2000.
- Strengths: Very detailed component models and reports. Good graphical interpretation of results.
- Weaknesses: no detailed cost models ($/Watt only).
- Contact: HOMER Energy 2334 Broadway, Suite B, Boulder CO 80304; Telephone: 720-565-4046; Email: info@homerenergy.com; Website: Homerenergy.com. Cost: $49 License fee.

Polysun

Polysun 4 is renewable energy system simulation software to configure and optimize solar and heat pump systems. Yield-forecasts are generated from integrated meteorological data. Detailed models used for system optimization and system comparisons.

- Expertise required: No special computer skills required.
- Users: Approximately 20,000 users internationally.

- Audience: Engineers, designers, component manufacturers.
- Input: Geographic location, component characteristics, energy load profile, costs for economic evaluation, horizon characteristics.
- Output: Output information: Solar fraction, hourly energy usage for system and components, economic analysis, et al. Output form: Tables of system and component performance data, customizable on-screen graphs and PDF report with system design and performance
- Computer platform: Windows Vista, XP, 2000, NT; at least 512 MB RAM; Internet connection.
- Programming language: Java.
- Strengths: Large customizable component catalog. Quick simulation time (typically less than two minutes). Especially good for solar thermal simulation and heat pump simulation.
- Weaknesses: PV is limited to grid-tie systems.
- Contact: Solar Consulting, 33 Water Mill Road, Marion, VA 24354; Telephone: 703-677-0581, Fax: 703-783-2399; Email: info@solarconsulting.us; Website: www.solarconsulting.us/polysun.html.
- Cost: Demo is free; Light $130; Professional $780, Designer $1950; Educational $130 (restrictions apply).

PV F-Chart

PV F-Chart models a daily profile of an average day for each month. It can model stand-alone battery systems and grid-tied systems; one- and two-axis tracking; and weather data for 300 locations.

- Expertise required: Requires training on the data collection and analysis process.
- Users: Unknown, but very many.
- Audience: Engineers.
- Input: Climate data; detailed solar system properties.
- Output: efficiency, load and fraction of load met by solar; Equipment cost, life cycle cost.
- Computer platform: Windows 2000.
- Strengths: Sound form of correlation. Detailed system models.
- Weaknesses: Limited to predefined system types.
- Contact: F-Chart Software; Box 44042; Madison, WI 53744; Telephone: 608-255-0842, Fax: 608-255-0841; Email: info@fchart.com. Website: www.fchart.com. Cost: $400 License fee.

PV*SOL

Software for the planning, analysis, and simulation of PVsystems. PV*SOL Basic provides array layout plan, photo image of roof plan, system production data, and financial analysis for grid-connected PV systems. PV*SOL Pro includes off-grid systems, and PV*SOL Expert includes three-dimensional visualization and shading analysis. Results saved to a file and presented in graph or chart form.

- Expertise required: No special expertise needed.
- Users: Over 1,000 users in Germany, Austria, and Switzerland. Now available internationally with the English version.
- Audience: Professionals: solar specialists, planners, engineers, heating technicians and plumbers, energy consultants. Educators: universities and research institutes.
- Input: Input roof areas or desired power output, select weather data by map or zip code from 1,000 sites, select modules and inverter from internet database.
- Output: Inverter and string sizing based on NEC requirements, wire sizes and losses, power and energy delivery. Preformatted reports in graph and chart form.
- Computer platform: unknown.
- Programming language: unknown.
- Strengths: Very detailed analysis supporting each step of engineering design and financing analysis.
- Contact: Valentin Software Inc., Temecula, CA ; Website: www.valentin-software.com; Telephone: (951) 530-3322, Fax: (858) 777-5526; Email: info@valentin-software.com.
- Cost: Basic $396; Pro $798; Expert $1,480.

PVSYST

PVSYST is software for sizing and simulation of grid-tied or off-grid PV systems. Includes database of PV components and meteorological data.

- Expertise: Practicing engineer or solar professional.
- Users: Unknown.
- Audience: Architects, engineers, researchers, educators.
- Input: For off-grid, power and run time of appliances; for on-grid, orientation of panels and some detail such as ventilation.
- Output: Chart of energy production.
- Computer platform: Unknown.
- Programming language: Unknown.
- Strengths: Considerable detail and extensive databases of required information.
- Weaknesses: none noted.
- Contact: pvsyst.com/en/software.
- Cost: $875, educational discount.

PV Watts

PV Watts is an on-line calculator of PV system energy production. Version 1 is based on selecting one of some 250 TMY weather sites, and Version 2 is based on satellite data processed on a 10-km grid. The hourly simulation corrects for temperature but does not model complicated utility rate schedules.

- Expertise required: No special training required.
- Users: Unknown.
- Audience: General interest, engineers, consultants, researchers, regulators.
- Input: Select site location in Version 1 or use longitude and latitude or zip code to indentify site on a map. Specify balance of system efficiency.

- Output: Monthly and annual energy delivery, monthly and annual cost savings.
- Computer platform: On-line internet application.
- Programming language: On-line internet application.
- Strengths: Quick easy savings estimate
- Weaknesses: Simple $/kWh estimate of cost savings; temperature coefficients can't be changed.
- Contact: Website: www.nrel.gov/rredc/pvwatts.
- Cost: Free.

Renewable Energy Optimization (REO, REOpt)

Renewable Energy Optimization (REO) is a simple spreadsheet program (see the example in Table 3-16) to evaluate life-cycle cost of a combination of renewable energy technologies at a site. The PV calculations use sunhour calculation similar to the example in the preceding text. The program combines resource data and incentive data from other databases, and simple heuristic estimates of cost and performance.

- Expertise required: Knowledge of energy data and units.
- Users: very few NREL staff planning projects at federal facilities.
- Audience: Renewable energy project planners.
- Input: GIS data on renewable energy resources via www.nrel.gov/gis. Incentives data via www.dsireusa.org; cost and performance of each renewable energy technology; site data, including square footage of each building type and utility bill information. User can change default values for PV efficiency.
- Output: Energy delivery by renewable energy systems, initial cost, O&M cost, life cycle cost. All outputs are in Microsoft Excel tables and are copied to a Microsoft Word report and Powerpoint presentation.
- Computer platform: Windows 2000, XP, Vista. MS Excel spreadsheet.
- Programming language: MS Excel, Premium Solver by Frontline Systems. REO 2.0 is MS Visual Basic version; REOpt is a subsequent but different model based on linear programming in Xpress.
- Strengths: Efficient processing of site data to identify and prioritize project opportunities.
- Weaknesses: Simple heuristic algorithms; no full engineering feasibility study.
- Contact: Andy Walker, National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401-3393; Telephone: 303-384-7531; Email: andy.walker@nrel.gov; Website: www.nrel.gov.
- Cost: Free for government use license only.

RETScreen

Natural Resources Canada provides this software for evaluating energy production and savings, costs, emission reductions, financial viability, and risk for various types of

TABLE 3-16. EXAMPLE OF REO-GENERATED SPREADSHEET WITH RESULTS FOR PHOTOVOLTAICS

PV rating (kW DC)	PV size (ft^2)	PV initial cost ($)	PV production incentive ($/year)	PV state tax credit ($)	PV federal tax credit ($)	Power level (kW AC)
55	3537	$253,228	$2,305	$25,000	$68,468	37

	PV energy delivery (kWh)	Capacity factor, AC (%)	PV utility cost savings ($)	PV annual O&M cost ($)	PV payback period (years)
January	5616	18.7%	$389		
February	5535	20.9%	$433		
March	7161	25.1%	$654		
April	6990	26.0%	$542		
May	7236	26.8%	$550		
June	6904	27.3%	$544		
July	6691	26.1%	$541		
August	6313	24.5%	$532		
September	6702	26.0%	$558		
October	6674	24.2%	$568		
November	5529	19.8%	$429		
December	5472	18.4%	$390		
Annual Total	76824	23.6%	$6,130	$1,049	26.9

renewable-energy technologies. The software (available in multiple languages) includes product and resource information, a detailed user manual, and a case-study-based college/university-level training course, including an engineering textbook. Software is capable of modeling any type of PV system including water pumping, off-grid, on-grid and hybrid systems.

- Expertise required: None; training material included in software.
- Users: More than 135,000 worldwide in 222 countries.
- Audience: Engineers, architects, technologists, planners, facility managers and educators.
- Input: Project dependent input in spreadsheet format. Climate data and product data included in software. Default and suggested values for all inputs via manual or project database.
- Output: Energy balance, emission analysis, financial analysis, etc. All outputs are in Excel and can be copied, printed, or saved to PDF format.
- Computer platform: Windows 2000, XP, Vista.
- Programming language: Excel, Visual Basic, C#.
- Strengths: Easy completion of feasibility studies for renewable energy and energy efficiency technologies.
- Contact: Natural Resources Canada, CANMET Energy Technology Centre-Varennes 1615 Lionel-Boulet, P.O. Box 4800, Varennes, Quebec J3X 1S6, Canada; Telephone: 450-652-4621, Fax: 450-652-5177; Email: rets@nrcan.gc.ca; Website: www.retscreen.net/.
- Cost: Free.

Solar Design Tool

This is an on-line tool that has two levels of detail: a Lite version that requires only a few basic site features and a Pro version that builds up system detail in terms of module strings and inverters.

- Expertise required: Some knowledge of solar resource and geometry nomenclature.
- Users: unknown.
- Audience: Design professionals.
- Input: Specify location in United States or Canada, other locations require that you enter the climate data. Roof dimensions and slopes.
- Output: Area, string sizing, array layout, PV energy production. Reports in both HTML and PDF format.
- Computer platform: Online website tool.
- Programming language: Online website tool; Google Map.
- Strengths: Supports layout required for actual design.
- Weaknesses: No battery model: on-grid systems only.
- Contact: Website: get.solardesigntool.com.
- Cost: Monthly access charge $7/month for Lite, $25/month for Pro, monthly or annual less expensive.

Solar-Estimate.org

Online calculator to estimate the costs and benefits of a PV system for a particular location and building needs. Links to current information and resources about solar energy data and programs.

- Expertise required: No special expertise required.
- Users: More than 2,500.
- Audience: Contractors, building owners, consultants, architects, engineers. Covers many professional services related to renewable energy and energy efficiency.
- Input: Location (state and country), energy usage (PV), water usage (domestic hot water), pool/spa size, utility, building type (residential or commercial/business). Many parameters have defaults but can be overriden by the user.
- Output: Results and information to the Web browser screen. Can be printed and copied/pasted.
- Computer platform: Any web browser.
- Programming language: PHP and MySQL databases.
- Strengths: Initial sizing and financial estimates for solar energy systems, including applicable incentive and tax credits.
- Weaknesses: Does not do detailed sizing or quoting of solar energy systems. Data covers United States only.
- Contact: Solar-Estimate.org, P.O. Box 4352, Santa Rosa, CA 95402-4352, United States; Telephone: 707-237-5204; Email: scott@energymatters.net; Website: www.solar-estimate.org.
- Cost: Free.

SolarGIS pvPlanner

Detailed model of solar radiation, geometry, temperature-dependent properties, different PV module types and different tracking options and shading.

- Expertise required: Some knowledge of solar resource and geometry nomenclature.
- Users: Unknown.
- Audience: Solar project prospectors, consultants, do-it-yourselfers.
- Input: Main inputs required: specify location with GIS mapping interface.
- Output: Solar insolation; PV energy production. Reports in PDF format
- Computer platform: Online website tool.
- Programming language: Online website tool; Google Maps.
- Strengths: Detailed database of solar resource information.
- Weaknesses: No battery model: on-grid systems only.
- Contact: GeoModel Solar sro; Telephone: 421 2 492 12 491; E-mail: contact@solargis.info; website: solargis.info/doc/54.
- Cost: varies depending on product up to 810 Eur.

SolOpt

Program to help energy auditors evaluate rooftop solar photovoltaics and solar hot water. Hourly simulation to determine the costs and benefits of PV systems for a particular location specified loads. Determines optimal use of available roof space by evaluating combinations of PV and solar water heating.

- Expertise required: Some training required.
- Users: Solar America Cities audit teams.
- Audience: Contractors, consultants, architects, engineers.
- Input: Hourly weather data; hot water use data; economic parameters; solar system properties.
- Output: Cost and savings of optimal combination of PV and solar hot water for a limited roof area.
- Computer platform: Windows PC.
- Programming Language: Microsoft Excel; Visual Basic.
- Strengths: Initial sizing and financial estimates for solar energy systems, including applicable incentive and tax credits. Detailed algorithms; 8760 Simulation.
- Contact: National Renewable Energy Laboratory; 1617 Cole Blvd, Golden, CO 80401; Telephone: 303-275-3000; Email: ian.metzger@nrel.gov; Website: http://www4.eere.energy.gov/solar/sunshot/resource_center/resources/solopt_optimization_tool. Cost: Free.

Solmetric iPV

An iPhone application that uses the camera and inclinometer positioning capability of an iPhone to trace the horizon. It then uses a database of climate data at sites to estimate monthly solar energy delivery, including the effects of shading.

- Expertise required: No special training.
- Users: Unknown
- Audience: Homeowners, solar enthusiasts.
- Input: Hourly weather data; hot water use data; economic parameters; solar system properties.
- Output: Monthly AC energy delivery, e-mail export
- Computer platform: iPhone 4 or 3GS.
- Programming language: iPhone app.
- Strengths: Quick easy evaluation of effect of shading objects. Built-in database of modules, inverters, worldwide weather data. Fixed, single-axis, and dual-axis tracking options.
- Weaknesses: It is difficult to move the camera smoothly to trace out the horizon- results are approximate.
- Contact: solmetric.com.
- Cost: $39.99

System Advisor Model (SAM)

Initially conceived to evaluate research priorities, SAM is based on a TRNSYS model engine with an interface to evaluate grid connected flat-plate and concentrating PV systems with several tracking options and detailed component models. It evaluates several different types of financing to represent both residential and utility-scale systems. Estimates PV system energy output, efficiency, capital and operation and maintenance costs, details of hourly rate schedules. Categories of cost are added up to calculate levelized cCost of energy ($/kWh) as the figure of merit.

- Expertise required: 1–2 days training recommended.
- Users: More than 3,000.
- Audience: Feasibility studies and policy-making, consultants, engineers. Not intended as engineering tool.
- Input: Weather data (TMY-2 in EPW format), utility rate structure, financial assumptions, incentives, component parameters, costs.
- Output: Financial metrics: levelized cost of energy, rate of return, payback period. Graphs and reports. Cash-flow detail and hourly data may be exported to Excel spreadsheet.
- Computer platform: Windows 7/Vista/XP or OS X 10.6 Intel or later; 500 MB disk space.
- Programming language: TRNSYS engine.
- Strengths: Database of PV module properties and price. Initial sizing and financial estimates for solar energy systems, including applicable incentive and tax credits. Sensitivity analysis.
- Weaknesses: Not intended as engineering tool, no details of wire sizing, etc.
- Contact: System Advisor Model; Website: sam.nrel.gov; Email Solar_Advisor_Support@nrel.gov.
- Cost: Free.

TRNSYS

TRNSYS stands for TraNsient System Simulation. A detailed energy simulation program with a flexible modular system approach, TRNSYS (TRaNsient SYstem Simulation Program) includes a graphical interface, a simulation engine, and a library of components that range from various building models to renewable technologies. TRNSYS also includes a method for creating new components that do not exist in the standard package.

- Expertise required: Specific knowledge of the TRNSYS software would be necessary to model PV systems.
- Users: Over 500.
- Audience: Engineers, consultants, researchers, consulting firms, architects.
- Input: Detail can extend beyond PV to whole-building and energy sytem models. Considerable detail regarding components and configuration of components into a system would be required before getting any results. Weather data. Input files can be ASCII text or can be generated by using a graphical user interface, known as the Simulation Studio.
- Output: Life cycle costs; monthly summaries; annual results; histograms; plotting of desired variables (by time unit). It is also possible to plot variables as the simulation progresses.
- Computer platform: Windows 95 or higher (98, NT, 2000, ME etc.) for TRNSYS interface programs (distributed source code will compile and run on any FORTRAN platform).

- Programming language: FORTRAN (although unnecessary for the use of standard components). It is also possible to write components in C++.
- Strengths: Modular approach and component library. Very detailed models. Extensive documentation. Graphical interface to drag-and-drop components for creating input files (Simulation Studio).
- Weaknesses: Software not specific to PV, so a lot of general training required to use for PV. Software does not answer common design questions, such as wire sizing.
- Contact: Solar Energy Laboratory, University of Wisconsin, 1500 Engineering Drive, Madison, WI 53706 United States; Telephone: 608-263-1589, Fax: 608-262-8464; Email: trnsys@sel.me.wisc.edu; Website: sel.me.wisc.edu/trnsys.
- Cost: Version 16, for commercial use $4,200; educational use is $2,100.

CODES AND STANDARDS FOR PHOTOVOLTAIC MODULES AND SYSTEMS

There are several organizations that promulgate standards and certification of photovoltaic modules and systems related to structural strength, electrical integrity, module and system performance, and safety.

ASCE American Society of Civil Engineers

ASCE promulgates the standard by which wind loads may be calculated for arrays of solar panels.

- ASCE 7 "Design Loads for Building and Other Structures."

ASTM International (Formerly American Society of Testing and Materials)

ASTM International (www.astm.org) was perhaps the first organization to issue standards related to PV and has hundreds of standards numbered 900 to 2000 that relate to photovoltaic materials, modules, and systems. Many of these relate to the physical strength and integrity of the electrical insulation. The PV testing laboratory at NREL must have looked like a torture chamber to incoming PV modules—with machines to freeze them, bake them, bend them, and shoot balls at them according to ASTM standards. Some of the most relevant ASTM standards are listed here

- E927-10 Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing
- E1036 - 08 Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells
- E1038-10 Determining Resistance of Photovoltaic Modules to Hail by Impact with Propelled Ice Balls
- E1171-09 Standard Methods for Photovoltaic Modules in Cyclic Temperature and Humidity Environments
- E1462-00 (2006) Standard Test Methods for Insulation Integrity and Ground Path Continuity of Photovoltaic Modules
- E1799-08 Standard Practice for Visual Inspection of PV Modules
- E1830-09 Standard Test Methods for Mechanical Integrity PV Modules

ASTM is also working on standards for installation of PV on rooftops; performance, weathering and aging; and accelerated life testing of PV modules, all of which will be useful when completed.

China Compulory Certification (CCC)

PV modules sold in China must have the CCC mark on the nameplate. The CCC mark indicates that the manufacturer complies with compulsory regulations related to safety and quality.

Conformite Europeenne (CE)

The CE mark on the nameplate is required of all PV modules sold in the European Union (rather than in the "European Economic Area"). Products must be tested by an external examination entity and certified that they meet all applicable standards and directives, mostly those promulgated by IEC (see IEC below).

European Solar Test Installation (ESTI)

CEC 503 Commission of European Communities (CEC) Qualification Test Procedures for Crystalline PV Modules EN13897

CEC 701 Qualification Test Procedures for Thin-film PV Modules

Factory Mutual

The FM symbol on a PV module nameplate indicates that the product has been tested by the organization for fire protection.

Federal Communications Commission (FCC)

Electronic devices, including such things as inverters, carry the FCC mark to indicate that they do not emit electromagnetic radiation that may interfere with communications and that their operation is not affected by electromagnetic radiation used for communication broadcast purposes.

Institute of Electrical and Electronics Engineers (IEEE)

IEEE (standards.ieee.org) really led the development of standards related to how a grid-connected PV inverter interacts with the utility system in terms of safety, performance, and utility operations. IEEE also promotes inter-operability of products. IEEE committee SCC21 develops standards related to PV. Some of the most relevant products of these efforts include:

- IEEE 519 Recommended Practices and Requirements for Harmonic Control in Electric Power Systems
- IEEE 927 Recommended Practices for Installation and Maintenance of Lead Acid Batteries for PV Systems
- IEEE 1145 Installation and Maintenance of Nickel Cadmium Batteries for PV Systems
- IEEE 1262 Recommended Practice for PV Module Qualification PV Module Performance and Reliability
- IEEE 1374 Guide for Terrestrial PV Power System Safety
- IEEE1547 Standard for Interconnecting Distributed Resources with Electric Power Systems
- IEEE1526 Recommended Practice for Testing the Performance of Stand Alone Photovoltaic Systems
- IEEE2030 Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with Electric Power Systems and End-use Applications and Loads

International Code Council (ICC)

ICC (www.iccsafe.org) concentrates on construction codes related to building safety. Several of their publications have sections with implications for design and installation of PV systems.

- IBC International Building Code (2012): includes fire-class ratings of PV modules and wind loading calculations.
- IRC International Residential Code for One- and Two-Family Dwellings (2012): includes electrical provisions related to PV systems.
- IFC International Fire Code (2012): requires certain markings on PV components; specifies required spacing and access around PV arrays on a roof; and special requirements for DC wiring.
- IgCC International Green Construction Code (2010): section 610 includes guidelines related to PV systems.

International Electrotechnical Commission (IEC)

Although headquartered in Switzerland, the IEC (www.eic.ch) has offices all over the world; and in the US the activities are coordinated through the American National Standards Institute (ANSI). Technical Committee 82 develops standards for PV. Some of the most relevant include:

- IEC 1194 Characteristic Parameters of Stand-Alone PV Systems
- IEC 1721 Resistance to Impact
- IEC 1727 Characteristics of the PV Utility Interface
- IEC 1829 On-site Measurement of i-v Characteristics of Crystalline Silicon PV Arrays
- IEC 16904 Photovoltaic Devices: measurement of i-v curve; measurement and reference requirements; and many other requirements related to the characterization of PV cells and modules.
- IEC 61215 Crystalline Silicon Terrestrial Photovoltaic (PV) Modules- Design Qualification and Type Approval (2005).
- IEC 61646 Thin Film Terrestrial Photovoltaic (PV) Modules—Design Qualification and Type Approval (2008)
- IEC 61853 Photovoltaic Module Performance Testing and Energy Rating (2010)
- IEC 61730 PV Module Safety Qualification (2004)
- IEC 62124 Photovoltaic Stand-Alone Systems—Design Verification (2004)
- IEC 61727 Photovoltaic Systems—Characteristics of Utility Interface (2004)
- IEC 61683 PV Systems—Power Conditioners-Procedure for Measuring Efficiency (2011)
- IEC 62109 Safety of Power Converters for Use in Photovoltaic Power Systems
- IEC 62446 Grid Connected Photovoltaic Systems—Minimum Requirements for System Documentation, Commissioning Tests, and Inspections (2009)
- IEC 62548 Installation and Safety Requirements for Photovoltaic Generators (2011)
- IEC/TS 62257 Recommendations for Small Renewable Energy Systems for Rural Electrification (2005)

International Standards Organization (ISO)

- ISO 9000, 9001, 9004 Standards for implementing management systems for quality, statutory requirements, and regulatory requirements.
- ISO 14001 Standards for managing Environmental Management Systems (EMS)

Intertek

Intertek is a testing organization.

National Fire Protection Association (NFPA)

The National Electric Code (NEC) published by NFPA (www.nfpa.org) is adopted by many jurisdictions (cities, counties) as compulsory requirements for any PV system. Every section of “the code” applies to PV installations, but the most relevant include:

- NEC Article 300: Wiring Methods and Materials
- NEC Article 480: Storage Batteries
- NEC Article 690: Solar Electric Systems
- NEC Article 705: Interconnected Electrical Power Production Sources
- NEC Article 720: Circuits and Equipment Operating at Less Than 50V

Any designer or electrician installing PV systems should know and observe all sections of the NEC. It not only ensures safety of the installer and the public; it also results in a quality installation that is more likely to deliver a long lifetime of service.

North American Board of Certified Energy Practitioners (NABCEP).

NABCEP (www.NABCEP.org) issues training and certification for PV system installers. Although voluntary, NABCEP certification may be required as proof of skill and experience as required to bid on projects as part of a solicitation. Specific certifications include;

- PV Technical Sales Certification
- PV Installer Certification

Occupational Safety and Health Administration.

OSHA (www.osha.gov) issues the regulation Safety and Health Regulations for Construction, which must be observed in order to satisfy requirements related to workplace and worker safety. It is OSHA that designates nationally recognized testing laboratories such as UL. 10 OSHA card certifies 10 hours of instruction and should be required of all construction site employees. 50 OSHA card certifies 50 hours of training and should be required of all permanent construction employees. There are many hazards involved in PV construction that require special training and personal protective equipment, including falls from heights, electrical hazards, arc-flash hazards, heat exhaustion and sunburn, and many others, each of which must be identified and mitigated through safe practices and protective equipment.

Technische Uberwach Verein (TUV)

TUV is a testing organization. TUV stands for the German words for "Technical Inspection Organization." They provide an independent third party to ensure safety and quality. They test solar panels and certify that they comply with IEC standards.

Underwriters Laboratory (UL)

The National Electric Code requires that almost any piece of equipment used in a PV system is "listed" by a nationally recognized testing laboratory, such as UL (www.ul.com) and most jurisdictions in theUnited States will not issue an electric permit unless all the components are so listed, including not only PV modules and inverters but wire, breakers, and all other components. UL ratings for common components of PV systems include:

- UL1703 Standard for Safety for Flat Plate Photovoltaic Modules and Panels
- UL1741 Inverters, Converters, Controllers and Interconnect System Equipment for Use with Distributed Energy Resources
- UL2703 Rack Mounting Systems and Clamping Devices for Flat Plate Photovoltaic Modules

OPERATION AND MAINTENANCE OF PHOTOVOLTAIC SYSTEMS

Low maintenance is a unique characteristic of PV modules. They are very reliable and last 20 years or longer. Operation and maintenance costs are reported at $12/kW/yr, or at 0.17 percent of capital cost without tracking and 0.35 percent of initial cost with tracking (Mortensen 2001). Another estimate approximates O&M of PV systems at $40/kW/year, including inverter replacement (Wiser et al. 2009). Data collected by Tuscon Electric Power from 2002 to 2006 remains one of the best sources of reliability data (Tucson Electric Power 2007), and reports annual planned maintenance at 0.04 to 0.08 percent of initial cost per year and unplanned maintenance at 0.01 to 0.22 percent of initial cost per year.

Most PV products are protected by tempered glass and require no regular maintenance. Cleaning is possible, but most owners rely on only rain to keep the array clean. Planned operation and maintenance tasks performed by site staff on an on-going basis include:

- Observe instantaneous operational indicators on the faceplate of the inverter to ensure that system is generating power when the sun is up, and that the amount of power being generated is typical of the conditions. For example, the power output in full sun on hot days should always be about the same, although lower than cool days. Observant maintenance staff can tell if something is wrong by noticing a sudden decrease in power output. Make this observation at noon or when the sun's rays are nearly perpendicular to the collector and post typical values for a hot day and a cold day near the inverter so that the present readings can be compared.
- Maintain a log of cumulative power delivery (kWh to date), and chart this value against date. Since we are looking at cumulative delivery, it does not have to be on an even or frequent interval and can be logged whenever convenient. Changes in the slope of this line should be explainable by season or weather.
- Document all operation and maintenance activities in a workbook available to all service personnel.

Planned tasks performed annually by site staff include:

- Walk through the PV array and check the PV modules for any damage. Report any damage to rack and damaged modules for warranty replacement.
- Check proper position of all disconnect switches.
- Inspect and maintain the wiring and condition of wire insulation and protective materials.
- Check tightness of mounting clamps. Reinstall any modules that have become loose.
- Determine if any new objects, such as vegetation growth, are causing shading of the array and move them if possible. Remove any debris from behind collectors and from gutters.
- Clean PV modules with plain water or mild dishwashing detergent. Do not use brushes, any types of solvents, abrasives, or harsh detergents.

- Check all hardware for signs of corrosion, and remove rust and re-paint if necessary.
- Open each combiner box and check that no fuses have blown and that all electrical connections are tight. An infrared camera is useful for identifying loose connections because they are warmer than good connections when passing current.
- Look for any signs of intrusion by pests such as insects and rodents. Remove any nests from electrical boxes or around the array. Use safe santitation practices because pests may carry disease.

Tasks performed by a solar contractor at intervals indicated by site conditions may include:

- Measure incident sunlight and simultaneously observe temperature and energy output. Calculate PV module efficiency as a function of temperature and calculate the balance-of-system efficiency. Compare readings with original efficiency of system.
- Replace any air filters on air-cooled equipment such as inverter.
- Retorque all electrical connections.
- Replace any electrical boxes that have extensive corrosion and repair or replace any damage to racks or modules. Replace any failed fuses or other components.
- Install any recent software upgrades to inverter programming or data acquisition and monitoring systems.

In addition to this regularly scheduled maintenance, unscheduled maintenance is required to address component failure. PV module failures are rare, the main causes being attempted theft or vandalism. The most common problems are related to the inverter. While PV module failures are responsible for only 6 percent of unscheduled maintenance costs, inverter failure accounts for 59 percent (Tucson Electric Power 2007). However, these costs are much, much lower than maintenance for any other type of generator, and inverters have gotten much more reliable in recent years. Until recently, inverters came with only a 1-year warranty, in contrast to the 20- or 25-year warranty on the PV modules. Then a European manufacturer offered a 10-year warranty and others have followed suit, such that a 10-year warranty on the inverter is a reasonable expectation.

Complete systems are often warranted by the installer for one year. Following that, manufacturer warranties for the PV modules (up to 25 years) and inverter (up to 10 years) as well as warranties on any other components transfer to the building owner for enforcement.

While PV module and the other components of a grid-tied PV system entail low maintenance requirements, the batteries of off-grid system require considerable maintenance. Flooded lead acid batteries require monthly maintenance of the electrolyte, and involve adding distilled water to replace that lost due to evaporation and hydrogen evolution. Sealed or valve regulated batteries do not allow the addition of water, and thus less regular maintenance, but still, they do require replacement and in the uncontrolled temperature conditions and deep-cycle duty typical of many off-grid system, they often do not achieve their design life and require replacement more often than expected. Batteries often come with a 1-year warranty, and may last as long as 10 years, although 3 to 7 years is more typical in my experience.

CASE STUDIES OF PHOTOVOLTAIC SYSTEM INSTALLATIONS

Here we consider two case studies, one large grid-tied PV system and a smaller off-grid system with batteries.

Grid-Tied Photovoltaic System on a Hospital in California

In 2007, the US Department of Veterans Affairs (VA) sponsored a "screening" study of all 317 facilities that it owns across the country. A screening is a study that uses simple calculations similar to those above, involving annual-average solar resource and utility rates. The screening identified hospitals in the urban areas of Southern California as the most cost-effective opportunities for photovoltaics installations due to a high solar resource, high utility rates, and progressive incentives for PV. Subsequently, I visited three of these hospitals in the Los Angeles area to measure the roofs, identify points of electrical connection, and prepare more detailed economic feasibility studies. I have also evaluated several other hospitals, and find hospitals to be good applications because they often locate mechanical equipment in large central plants, leaving roof areas open for PV, and they also have large electrical service near the roof, providing places to tie into the conventional utility system.

The VA issued a procurement using the GSA Schedule, which facilitates purchases for federal agencies, and SunWize Technologies Inc. was selected to furnish and install a complete PV system on the Jerry L. Pettis Memorial VA Medical Center in Loma Linda, California. The project was managed by Loma Linda VA Health Care System Energy Manager Larry Barrett. The system was completed in 2008 and consisted of 1,548 Sanyo HIPBA3 PV modules wired in series strings of 8 per string. These modules have a high efficiency of 16.6 percent due to their construction (heterojunction with instrinsic thin layer, as described in the section regarding different types of PV earlier in this chapter). Each module is rated for P_{STC} = 195W under STC conditions with v_{mp} = 55.3 Volts and i_{mp} = 3.53 Amps at maximum power point, and each string of 8 produces v_{mp} = 443.4 Volts. This satisfies the 330-volt minimum input voltage of the inverter, yet is less than the 600-volt limit imposed by code and the UL-listing of the system components. The system is a bi-polar configuration, which means that half of the combiner boxes are wired with the positive fused and the negative grounded, and the other half with the negative fused and the positive grounded. Thus, the voltage available to the inverter is twice that of each series string. The wires from each combiner box are, in turn, combined together at a main combiner box at the location of the DC disconnect switch.

The panels are mounted at a 20-degree tilt on a mounting system manufactured by Sunlink that minimizes roof penetrations. This tilt angle has an annual average solar resource of 5.5 kWh/m^2/day, which is less than the 5.6 kWh/m^2/day of a 34-degree tilt, but it reduces the wind load on the modules and the 20-degree tilt has its maximum solar incidence of 7.1 kWh/m^2/day in July (versus 6.6 kWh/m^2/day for 34-degree tilt) (Marion and Wilcox 1994), thus maximizing power delivery during peak air-conditioning times.

Summing the ratings for each module, the system is rated at $P_{STC} = 308.88$ kW under STC conditions, and $P_{PTC} = 282$ kW under PTC conditions. The inverter is a Solaron inverter manufactured by Advanced Energy Industries and is rated for 333 kVA. The wires leaving the inverter pass through an AC disconnect switch and feed power to a 480V_{AC} 3-phase, 4-wire (Y) distribution panel. Despite the fact that the PV covers a large part of the roof, it provides a small fraction of the power required of the hospital.

The inverter was placed in the middle of the roof, which is located about 200 feet away from closest edge of the building. That would have required a large crane to pick up and deliver the inverter, which weighed more than a ton. Such a large crane would be expensive and difficult to transport on California highways. SunWize hired a company that delivered a Vietnam-era Huey helicopter by flatbed truck and used it to lift the inverter into its final destination. The lift was done on a Sunday, and through coordination with safety staff to clear the path of delivery from fourth floor down to the first floor. It took 10 minutes to pick up and deliver the inverter.

Figure 3-22 shows Larry Barrett at the installation. Bob Hlavity of SunWize and I inspected the system at 2 p.m. on August 15, 2008, and the system was producing $P_{mp} = 230$ kW with $I_C = 900$ W/m^2 insolation and $T_{ambient} = 38$ C (101 F). Again on April 19, 2011 at 11 a.m., it was producing 111 kW at 407 W/m^2 solar and 17 C (63 F) ambient temperature. The system was supplied with a data monitoring system by Fat Spaniel Inc. which logs system performance and environmental conditions. Figure 3-23 is the monthly energy delivery of the system as reported by the monitoring system. Over the course of the first year year of operation, the system energy delivery was measured at $E_{solar} = 497{,}288$ kWh/year.

Figure 3-22. Facility manager Larry Barrett inspects the PV system on the roof of the Jerry L. Pettis Memorial VA Medical Center in Loma Linda, California. (Photograph courtesy of Larry Barrett)

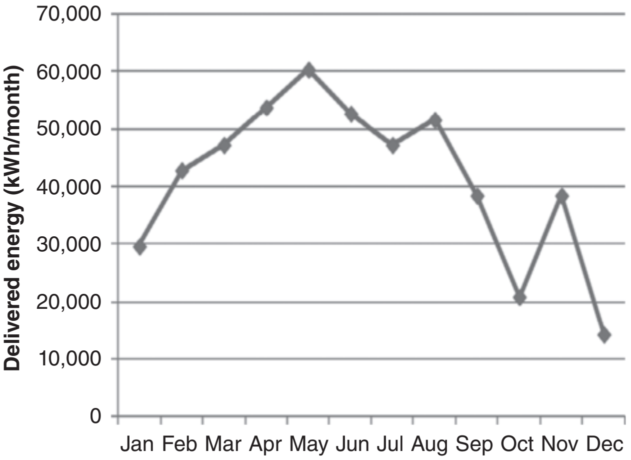

Figure 3-23. Monthly energy delivery from April 2009 to March 2010 as measured by the data monitoring system on the PV system at Jerry L. Pettis Memorial VA Medical Center. (Figure by the author)

The simple hand calculation above results in a comparable value: Esolar = Psolar*IC/(1 kW/m^2)*η_{bos} = (308.88kW)*(5.5 kWh/m^2/day)/(1 kW/m^2)*0.77 = 477,459 kWh/year.

Annual utility cost savings are estimated at approximately $C_{savings}$ = (497,288 kWh/year)*(\$0.125/kWh) = \$62,000/year. A production-based incentive of \$0.37/kWh paid by Southern California Edison utility company for the first five years following installation would have a total value of approximately \$920,000. Assuming a cost of approximately C_{intial} = \$2,000,000, we project a simple payback period of (\$2,000,000 – \$920,000)/\$62,000 = 17.6 years. Using a present worth factor of 17.1 years (25-year analysis period and 4 percent discount rate), the savings to investment ratio (SIR) is 1.0, which meets that definition of cost-effectiveness, albeit just barely. The utility cost may be expected to go up over time, and the system helps the VA meet their environmental goals:

> "To date, our 309 kW PV system is trouble free and still performing like new with very little maintenance requirements. With the 10-year warranty, SunWize had been tracking its performance and always on top of the situation when problems arise. VA Loma Linda is now in the process of expanding the PV system to total of 2 MW by constructing solar carports and adding more arrays on the hospital roof." (Larry Barrett, Energy Manager, VA Loma Linda Healthcare System)

Off-Grid Photovoltaic System at a Remote Campground

Kirby Cove Campground, part of Golden Gate National Recreation Area, is located in Marin County, California. Energy Manager Jim Christensen was faced with an estimated \$160,000 cost to replace an old powerline to the site, and did not want to consider diesel or propane generators because of the fuel and maintenance costs, and because of the noise and pollution generators would introduce onto this tent campground. In 1998 I installed instruments to measure the load and resources (solar, wind) at the site. The campground is occupied mainly in summer, and the load imposed by the travel trailer of the campground host was estimated at 2 kWh/day. Global solar radiation averaged $I_{\text{horizontal}}$ = 5.18 kWh/m^2/day, and diffuse radiation was a large part of this at $I_{\text{horizontal,diffuse}}$ = 3.14 kWh/m^2/day. The ambient temperature averaged T_{ambient} = 16.3C over the summer months. The global radiation was lower and the diffuse radiation higher than other sites due to the fog that develops in the summer. Renee Azerbegi, then working a Lawrence Berkeley National Laboratory, and I evaluated several alternatives, including wind power and even tidal power (Azerbegi et al. 1999). Due to the reliability and the low-profile appearance, photovoltaics were preferred among all the alternatives we evaluated. A competitive solicitation was issued, and Lyle Rawlings of Fully Independent Solar Inc. was selected to design the system. Solar Depot in San Ramon, California supplied and installed the PV modules, batteries, and inverter. The system consisted of nine PV modules for a rated power of P_{STC} = 960 W_{DC}. Storage is provided by sealed, valve-regulated deep-cycle lead acid batteries with a total storage capacity of 375 Ah at 24 Volts. The 24 V_{DC} is converted to 120_{AC} by a Trace 1024 inverter capable of delivering 4 kW_{AC} maximum peak power draw. Charging of the batteries is regulated by a charge controller, which also involves a low-voltage disconnect to disconnect the load when the batteries reach a low voltage set point.

Figure 3-24 shows how the system was constructed with the PV modules forming the roof of an enclosure, and the batteries, inverter, and controls inside the enclosure. Power is delivered by an underground power line to a pedestal near the campground host. Figure 3-25 shows one week of operation in June 2011, which illustrated the details of system operation (Walker et al. 2002). The campground host uses any amount of power day or night; the load rarely goes below 90 W, indicating that some "vampire" loads are drawing power even at night or when the host's trailer is unoccupied. As the load draws power, the battery voltage declines, indicating its state-of-charge. However, when the power from the solar array exceeds the load, the battery is charged back up, and its voltage increases. At three times during this week, at hours 13, 85, and 109 in the chart, the batteries drop below the set point of the low-voltage disconnect and the load is disconnected. Users of power would then have to wait three to five hours for the sun to come up in the morning and for the PV array to charge the battery again before the system would automatically reconnect and resume power to the load again.

Figure 3-24. Photograph of 960 W PV array at Kirby Cove Campground in California. Deep-cycle batteries, inverter, and balance of system are located in the shed enclosure under the solar panels (Photo by the author).

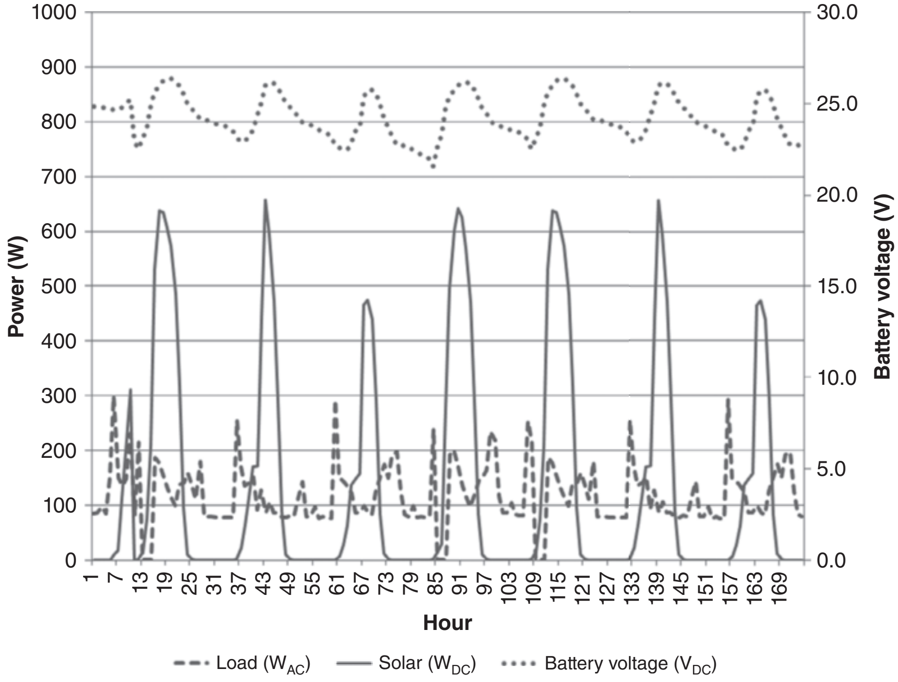

Figure 3-25. Data collected from June 16 to 23, 2001 shows details of operation of the remote PV system at Kirby Cove, California. (Figure by the author)

Example

Procurement Specifications for Grid-Tied Solar Electric (Photovoltaic) System

The following text is a sample of procurement specifications typical of what might be issued in a request for proposals or subsequently in a contract for design and construction. These specifications were originally produced for the US Department of Energy Federal Energy Management Program in 2003 by assembling the best of 3 or 4 projects, and involved review by both building managers and solar industry professionals. Subsequently, they've been updated by the author based on recent project preparation and input from vendors. These specifications are not inclusive of all the considerations that must be addressed in your particular project. These are offered only as encouragement that you can indeed get all your requirements down on paper and to give you a head start on that task.

Part 1-General

1.1 Summary

The scope of this solicitation is for a complete roof- or ground-mounted photovoltaic system with all design work, equipment and materials, installation, testing, warranty, training, and all appurtenances to make the photovoltaics system complete and operational. Depending on the details of the design, the system shall have power rating under Standard Test Conditions (STC) of ____ kW. The system will be grid-tied (connected to the utility system). There will be no energy storage devices (e.g., batteries) used in this system. This project shall meet all technical requirements of this Statement of Work and other specifications included that apply. The project shall comply with all applicable codes and standards as well as any requirements imposed by utility regulations and policy.

1.2 Description of Work

The contractor shall perform all professional services as necessary to provide the government with a complete design package, including the requirements outlined in this Statement of Work. The design package shall include specifications, calculations, and drawings which will be turned over to the building owner. After owner approval of the final design package, the contractor shall furnish all equipment and materials; and construction labor; and provide all necessary permitting to successfully install the photovoltaic system.

1.3 Related Documents

Describe any other sections that may govern work related to the PV system.

1.4 References

The publications listed below form a part of this document to the extent required to meet the intent of the design:

- Institute of Electrical and Electronic Engineers, Inc. (IEEE) standard 1547 utility interface of "Utility-Interactive" inverter.
- Underwriters Laboratory "UL Standard 1741, Standard for Static Inverters and Charge Controllers for Use in PV Power Systems"
- National Electric Code (NEC) all sections that apply, including Article 720; Article 690, 90-2—Electrical installations of PV Equipment. Recommended installation practices (most recent issued version)
- UL 1703 Flat-Plate PV Modules and Panels
- UL 1741—Standard for Static Inverters and Charge Controllers for
- Use in Photovoltaic Power Systems
- FM Approved—Fire Protection Tests for Solar Component products
- ANSI Z21.83 (solar PV performance and safety)
- NFPA 853 (solar PVs near buildings)
- NFPA 70 (NEC) (electrical components)
- ASCE/ SEI-7—American Society of Civil Engineers—"Minimum Design Loads for Buildings and Other Structures"
- NRCA—National Roofing Contractors Association—Waterproofing Guidelines
- IEC 16446 Inspection, PV Array Testing, and Performance Evaluation of PV Systems.

1.5 Design Requirements

Develop a design for a new photovoltaic system for the ground or roof of the Facility. The image below indicates the existing site plan and roof layout with potential proposed location for photovoltaic arrays indicated. This drawing is meant for informational purposes only and must be field verified by the contractor. Care will be necessary to avoid shading by objects on the roof and trees, and some tree trimming or removal may be necessary to avoid shading of the array, but that should be limited to the greatest extent possible. Locate equipment near the electrical service entrance to the building, which facilitates electrical interconnection of the PV output. An assured clear distance (work zone) shall be maintained around the existing equipment for future servicing by others. For rooftop installations where there is no parapet or the parapet is less than 42″ tall, a 6″ safety zone from the roof edge to the PV system shall be maintained. A 3′ clear path of travel shall be maintained to and around all rooftop equipment. Inverters shall have permanent access walkways to facilitate monitoring and maintenance.

The PV system shall be sized to fit within the available roof and ground areas, with the designer confirming that the size determined by the design is compatible with the site geotechnical capacities, roof structure, building load, building electrical service, and utility policy. Ground-mounted panels are to be a minimum of two feet above ground level to facilitate future maintenance. Integrate lightning protection with building lightning protection system, and provide surge protection on all electrical systems. Aesthetics and the preservation of any historic, cultural, and natural resources of the site shall be addressed through consultation with the Owner during design.

Within 10 calendar days after receipt of the contract award, a meeting will be attended by the government team members and the contractor's personnel. At a minimum, the prime contractor's project manager and foreman, the primary designer, and a representative of any subcontractor performing over 25% of the work must attend. The meeting will be held at the project location. The purpose of the meeting will be to discuss the contractor's plan for completing the design and construction and to agree on a timeline for completion. A walk-through of the site will occur at the end of the meeting. Possible locations of equipment and utility interconnection will be established during this site visit.

Sample Specifications Figure 1. Facility aerial site plan and roof plan of facility with possible PV array location indicated (enter your own figure here).

SAMPLE SPECIFICATIONS TABLE 1. SIZE OF AREA ON THE FACILITY ROOF AND GROUND IDENTIFIED AS LOCATION FOR PV ARRAY, INDICATED ON SAMPLE FIGURE 1 (ENTER YOUR OWN AREAS HERE).

Array	Length (ft)	Width (ft)	Area (ft^2)	Surface slope, tilt (deg)
Area #1				
Area #2				
Total area				

1.6 Performance Requirements

Contractor shall prepare a roof-condition report to inform decisions regarding type of roof mounting system and a geotechnical report for the design of shallow-pier foundations. The report will observe the type of soil at different depths, the load bearing capacity, and the depth of groundwater. Mounting system shall be designed to meet requirements determined in the geotechnical report and roof condition report and to minimize site maintenance requirements into the future roof penetrations. Conduit penetrations through building fabric shall be minimized and limited to one location, or as few locations as possible. Roof penetrations shall be designed and constructed in collaboration with the roofing professional or manufacturer responsible for the roof and roofing material warranty for the site, and in such a way that the roof warranty is not voided. The number and size of the penetrations necessary to extend the power and control cable into the building must be kept to a minimum and grouped in a single location when practicable. All weatherproofing of penetrations shall be compatible with the roof warranty or if roof has no warranty then accepted best practice.

The Contractor shall provide a roof ground or ground-mounted system with a fixed tilt that maximizes annual energy production, per industry practice for this geographical area, or flush on roof within constraints of available space and shading. Consider south facing at a tilt equal to the local latitude, although other tilt angles will be considered based on wind loading and other considerations. Power provided from the system shall be 277/480 volt 3-phase 4-wire or other voltage as field confirmed by contractor at the point of electrical interconnection. PV system must be compatible with the onsite distribution system. Contractor shall identify alternative points of connection location for selection and approval by the Owner. Estimated energy delivery (kWh) shall be provided for the systems for each month of the year and total for the year at the delivered voltage. Deliver calculations to support the estimate. The photovoltaic panel system including supports and power conductors shall not interfere with roof drains, expansion joints, air intakes, existing electrical and mechanical equipment or utilities, existing antennas, and planned areas for future installation of equipment shown on drawings.

Installation and equipment shall comply with all applicable wind, snow, seismic, structural, and electrical codes. Products that are listed, tested, identified, or labeled by UL, FM, ETL, or other National Recognized Testing Laboratory shall be used when available. Nonlisted products are only permitted when listing does not exist. Nonlisted products must be identified as such in all submittals. The contractor shall provide materials that are recyclable, contain recycled materials, and that are EPA or Energy Star rated if they are available on the market.

1.7 Submittals

Submittals shall be delivered to the Owner based on the project schedule. For each submission, the Owner reserves the right to make comments and request changes after the receipt of the submission. As part of its review, the Owner may offer submission reviews to local code officials or outside experts. Each submittal shall be approved by the Owner prior to subsequent submittals. The Contractor shall respond to all design review comments in writing, indicating one of the following: (1) Adoption and action taken, (2) Adoption with modifications and action taken, (3) Alternative resolution and action taken, or (4) Rejection. In cases other than unqualified adoption, the Contractor shall provide a statement as to why the reviewer's comment is inappropriate. Rejection items shall not go forward to the construction phase until adequate resolution to the rejected items have been approved by the

(continued)

Contracting Officer. Design review comments shall not relieve the Contractor from compliance with all applicable codes and standards and the terms and conditions of this contract. Contractor's comment resolution shall be transmitted to the Owner within seven (7) calendar days of comment receipt and incorporate discussions from the scheduled design comment review meetings.

If the contractor believes that any Owner design comments or requested changes will result in a change in the contract cost, he/she shall notify the Contracting Officer and Contracting Officer's representative within seven (7) calendar days of receiving the comment(s) and provide detail cost estimate of anticipated contract modifications.

Submittals shall be made to the contracting officer's representative and shall contain four (4) copies and 2 CDs containing copies of all the materials. The Contractor shall combine all product data submission material into hard copy manuals for reference during all phases of construction. Shop drawings shall be bound with product data. The Contractor is required to provide: (1) conceptual design; (2) construction documents and engineering calculations that are signed and sealed by a licensed architect/engineer; (3) submittals for materials and products; (4) construction schedule with dates of completion of key milestones; (5) quality control plan; (6) safety plan; (7) utility interconnection agreement and rebate application; (8) reports of inspections and tests; 9) commissioning report; (10) training materials (including videotape of live training) for building operating staff; and (11) operation and maintenance manual.

Conceptual design. The contractor shall provide the government with concept design drawings. The drawings must indicate the proposed location of the PV array and access points along with a one-line electrical diagram showing inverters, transformers, meters, and interconnection locations. All drawings shall be submitted with dimensions shown in English units.The concept design shall include major equipment information, proposed installation/interconnection information, and performance characteristics of the system. At a minimum, the concept information shall include the following information about equipment: (1) physical dimensions and estimated power rating per module; (2) estimated number of modules; (3) total array output (STC-rated power, open circuit voltage, short circuit current); (4) number of inverters, type and mode of operation (utility interactive); (5) inverters continuous ac rating, (6) estimated total inverter output; (7) estimated inverters peak efficiency and efficiency at various output levels; (8) mounting rack equipment— type and material of construction; and (9) size of conductors and conduit. Conceptual design shall include the following information about the installation: (1) solar electric array orientation (degrees) relative to the building structure; (2) solar electric module tilt (degrees), (3) placement and mounting of inverter system; (4) mounting structure layout, including roof ground penetrations and structural attachments; (5) estimated number of roof penetrations; and (6) routing of conduit to connect all components. Conceptual design shall provide confirmation that the PV systems will be designed to comply with any requirements imposed by the utility for interconnection with the utility system.

Schematic design; detailed design and construction documents: upon approval of the concept design by the owner, contractorshall provide design services and submit 25 percent schematic design submission. The Owner will review the design submittal and provide written comments within 10 days. Contractor shall then prepare a 75% design development submission. The Owner will review this submittal and provide written comments within 20 days. Contractor shall then prepare a 100 percent check set submission and a construction document submission.

A full set of architectural specifications shall not be required for this project. However, specifications which express all information that demonstrates sufficient detail for approval by the Owner and to direct the construction work outlined in this Statement of Work shall be required. The specifications package shall be coherent enough that any contractor not familiar with the project would be able to construct the project design. The specifications shall include all equipment information, proposed installation/interconnection information, and performance characteristics of the system.

Provide drawings for each discipline required (electrical, roofing, structural, etc.), with separate plans for new work and demolition as well as special types of drawings where necessary, such as enlarged plans, equipment curbing and flashing details, ground mounting and roof penetration details, etc. Detailed drawing shall be provided, showing base and structural supports planned for supporting the array—i.e., footers, pylons, support, etc. Drawings shall clearly distinguish between new and existing work. Each drawing shall indicate project title, project number, building name, building address, A/E firm, A/E's address and/or phone number, contract number, drawing title, drawing type, drawing number, and key plan. A cover sheet shall be provided and shall include a list of the drawings, legend, vicinity map, and location map, in addition to all items required for each drawing. Each A/E submission shall be clearly dated and labeled (e.g., 75% design development submission, 100% percent check set submission, construction document submission, as-built drawings, etc.). Each drawing sheet submitted shall include a graphic scale in the lower right-hand portion of the sheet. The final set shall be stamped by a registered engineer and/or registered architect for the jurisdiction in which the building is located. At a minimum, the following drawings are required: (1) Site plan including utility locations and connections shall show staging, lay-down areas, and phasing requirements; (2) Electrical plans including wiring diagram and utility interconnection details; (3) Roof or ground mounting plan—showing the full layout of the system and detailing any obstacles that must be permanently or temporarily removed or relocated; (4) Waterproofing details for roof penetrations;. (5) Any other drawings that may be required to install a complete project.

As-built drawings and information: A final set of as-built drawings shall also be provided to the Owner detailing the system as installed, including any deviations from the plan design. Should the Owner determine that variations exist between finished construction and the as-built drawings, the contractor shall correct drawings to the satisfaction of the Owner. The contractor shall submit six (6) hard copies and two (2) CDs containing the "as-built" drawings and specifications as CAD and PDF files. The as-built drawings in CAD shall comply with the government National CAD Deliverables Policy.

Calculations: The contractor will provide the following calculations: (1.) System electrical calculations: provide with design development and again with 100 percent check set. (2.) Energy production calculation showing estimated monthly and yearly energy output for each system (using PVWatts or equivalent calculation tool). (3.) Voltage and current details of array, confirming that voltage limits ($600V_{DC}$) and conductor sizing (amps) are observed. Include the effect of temperature in calculations. (4.) Geotechnical calculations for the design of pier foundations. (5.) Roof structural loading calculations. These calculations shall specifically address roof loading from the PV array and confirmation that the loading does not exceed existing roof framing capacity as determined by analysis by contractor structural engineer.

Registration seals: Each final working drawing and each submitted specification and calculation document shall be signed by, bear the seal of, and show the certificate number of the architect or engineer who prepared the document or is responsible for its preparation.

Utility interconnection agreement: The Contractor is responsible for identifying and preparing required submissions for obtaining the interconnection agreement from the utility. The Owner will sign the interconnection agreement, not the Contractor. The documents must be provided to the Owner with sufficient time for legal and administrative review. Upon completion of the system installation, all utility and permitting requirements shall be in place so that the system may be operated.

Permits: Contractor shall obtain all required permits and licenses and arrange for inspection of work by all authorities. Deliver, without additional cost to the Owner, such certifications of inspection and approval as are required and pay all charges and fees in connection with the work.

Applications for rebates and incentives: Contractor shall provide all necessary information and assist in facilitating access to utility or other rebates that may be available for this installation.

1.8 Quality Assurance

Contractor shall prepare a Quality Control Plan (QCP) to identify each item or system to be tested, exact test(s) to be performed, measured parameters, inspection/testing organization, and the stage of construction development when tests are to be performed. Each inspection/test shall be included in the overall construction schedule. The Contractor is not relieved from required performance tests should these not be included in the plan. The QCP assures the Owner that product delivery, quality and performance are as required so that those tests can be performed before it is too late. It also serves as an inspection coordination tool between the Contractor and the Owner. Examples of these inspections/tests are: testing each module before installation; testing each series string; the final test / inspection for overall performance compliance of the system. Results from tests and inspections shall be submitted within 24 hours of performing the tests and inspections. The QCP shall be prepared and submitted within 21 calendar days of the post award conference meeting and prior to any construction on-site.

1.9 Delivery and Storage

Protect materials during transport with suitable packaging and handling. Inspect all materials upon delivery. Do not deliver materials until provisions for site storage and protection are available. Materials shall be stored out of contact with the ground in weather-tight coverings with a slight slope so that water does not pool on the cover. Do not stack other materials on top of the PV modules.

Part 2-Products

2.1 General Equipment Requirements

- Provide standard products manufactured and intended for the purpose and that have been in use by industry for at least one year. Provide each piece of major equipment (PV modules, inverter) with manufacturer's name, address, type, model, serial number on a permanent plate affixed to the item. Warning labels shall be posted on the source circuit conduit, combiner boxes, DC and AC disconnects, control panels and junction boxes indicating that the circuits are energized by an alternate power source independent of utility-provided power. All PV hardware components shall be either stainless steel or aluminum. PV Structural components shall be corrosion resistant (galvanized steel, stainless steel, composites, or aluminum).

(continued)

- All electronics enclosures shall be rated as NEMA 3R or better and have superior strength and corrosion resistance properties.
- No wood products will be permitted.

2.2 Solar Electric PV Models

PV Modules shall meet or exceed the requirements of Underwriter Laboratories (UL) Standard 1703 Standard for Safety for Flat-Plate Photovoltaic Modules and either IEEE Standard 1262-1995 IEEE Recommended Practice for Qualification of Photovoltaic (PV) Modules and Panels or IEC 1215 Crystalline Silicon Terrestrial Photovoltaic (PV) Modules—Design Qualification and Type Approval. Supplied equipment must be rated and warranted to withstand and operate under the temperature extremes and humidity conditions of the site. PV modules shall be provided with a nameplate with key electrical design information such as rated power, short circuit current, open circuit voltage, and with a datasheet including more details such as coefficients relating how these parameters change with temperature. Two (2) extra PV panels shall be provided for replacement parts kept on-site.

2.3 Inverter and Controls

The Inverter shall have at a minimum the following features: UL/ETL Listed; designed specifically for utility grid interconnection of photovoltaic arrays and be capable of automatic, continuous, and stable operation over the range of voltages, currents and power levels for the size and type of array used; peak efficiency of 95% or higher; Inverter shall have operational indicators of performance and have built in data acquisition and remote monitoring. The inverter shall be capable of parallel operation with the existing AC power. Each inverter shall automatically synchronize its output waveform with that of the utility upon restoration of utility power. Inverters shall be have UL 1741 certified, for approved list of inverters see www.gosolarcalifornia.org/equipment/inverter.php. The inverter system should be equipped with the following visual indicators and/or controls: operating mode setting indicator; operating status indicator; DC voltage; AC Power output. Power provided shall be compatible with on site electric distribution systems. The inverter and system shall utilize means to shut down the inverter during night time to avoid energy usage at night.

2.4 Wiring

All interconnecting wires shall be copper and sized to carry the expected current including oversizing factors for temperature and conduit-fill according to code requirements. All outside wiring shall be rated for wet conditions. Wiring in readiliy accessible locations shall be protected in metallic conduit except that the last three feet may be liquid-tight non-metalic conduit to allow for movement and maintenance. Insulation on any wiring located in areas with potential exposure to ambient temperature shall be rated at 90 C or higher. All junction boxes shall be aluminum, stainless steel, or non-metallic with hinged covers and NEMA 3R or better rating.

2.5 Monitoring System

The PV system shall include monitoring system to display system performance to the Owner. Monitor by an IP addressable device and display graphically in a user-friendly manner the following parameters: DC voltage; DC current; DC power; solar irradiance; PV cell temperature; ambient air temperature; show status of all equipment; Instantaneous AC power (kW); cumulative daily, monthly, and annual energy delivery (kWh). Data shall be available both in real time and archived in fifteen-minute averages. All monitoring hardware and monitoring equipment shall be provided by the contractor.

System performance shall allow display during different monitoring periods from 1 hour to 1 year (hourly for a day, daily for a month, monthly for a year). Provide networking equipment, engineering, programming, wiring, and software to allow remote connection by the Owner to the monitoring system.

If not provided by functionality of the inverter, contractor shall supply and install a meter to monitor energy performance of system. Meter shall be a solid state advanced meter with the following features: nonvolatile memory capable of storing parameters for 30 days, using Ethernet port, accuracy meeting ANSI C.12.16, TCP/IP communication, and Modbus IP protocol. The electrical metering shall be compatible with the software currently used by the Owner for other meters at the site. All electric meters shall be installed with shorting bars to use to short induced current from the current transformers to ground and to facilitate repair and replacement without the need for an outage. Fuses shall be installed in series with the power meter voltage references. Meters shall be installed in the main distribution panel (MDP) when possible. Meters shall not be mounted to the transformer housing without prior approval when there is no other reasonable place to mount it. All electric meters shall be connected to the Owner system thru the Owner network in accordance with the the Owner's direction. The following shall be performed when adding the meter: definition of the meters in the system database; development of reports including any custom reports which may be required; end-to-end testing of the new meters; Addition of the meters to the graphics screens in the Owner software systems; and Addition of added meter to existing custom reports that are applicable.

2.6 Transformers

Use of transformers shall be avoided by selection of inverter and configuration of system, but if needed, stand alone boost-up or isolation transformers shall have an efficiency greater than 97%. Exterior Transformers shall be housed in a NEMA 3R enclosure and be pad mounted. Location shall be approved as a part of the design process.

Part 3- Execution

Site data collection: examine the building roof and ground areas to verify readiness for construction. If any condition is found that prevents proper execution of the work, the installer shall report such conditions in writing to the owner and shall not proceed until conditions are corrected.

3.1 Installation

Construction: Perform all construction necessary for the successful installation of the system based upon the design generated according to the Design Requirements above. The contractor shall prepare a construction plan producing a minimum disruption of day-to-day activities, utilities, services, etc. Specifically address the means to keep the existing building accessible and operational by means of location and / or phasing of the work and laydown areas.

Locate and avoid underground utilities coming into the building when digging array foundations or trenching in a new buried conductor.

System wiring shall be installed in accordance with the provisions of the NEC.

Areas where wiring passes through ceilings, walls or other areas of the building shall be properly restored, booted, sealed and returned to its original condition. Thermal insulation in areas where wiring is installed shall be replaced to “as found or better condition.” Access doors to these areas shall be properly sealed and gasketed.

All wiring splices shall be contained in UL-approved junction boxes. Wiring connections shall be properly made, insulated and weather protected. All power wiring shall be attached to the system components by the use of strain reliefs or cable clamps, unless enclosed in conduit. Conduit shall be equipped with expansion joints where ground-movement or thermal expansion and contraction are possible. All modules installed in a series string shall be installed in the same plane. Panel installation design shall allow for the best ventilation possible of panels to avoid adverse performance impacts due to high temperatures.

The aesthetics of the overall installation are important to the Owner. To create a uniform appearance of the array, spacing between individual modules and panels should be kept to a minimum. As much as possible, all mechanical hardware, conduit, junction boxes and other equipment should be concealed beneath and/or behind the array. PV modules shall be properly installed according to manufacturer’s instructions and code requirements. Module frames shall not be modified by drilling holes. The array layout should be consistent with the ordering (and labeling) of source circuits in the array combiner boxes. Ease of access for array troubleshooting and maintenance is desired by allowing access to the back of the array for module junction box servicing, and removal/replacement of individual source circuits (panels) and modules if necessary.

Each inverter and associated controls shall be properly installed according to manufacturer’s instructions. Install inverters and control panels in most optimum locations with appropriate environmental protection, including any venting and weather sealing required by the electronics enclosed. If inverters are mounted outside they shall be shaded from direct sun to the extent practical.

3.2 Inspection, Testing, and Commissioning

The Contractor shall perform inspections and tests throughout the construction process including: existing conditions/needs assessments, construction installation placement/qualification measurements and final inspections/tests performance certification. Periodic “Quality” inspections shall also be conducted to support progress payments as identified in the contractor’s quality control plan. All inspections and tests, to verify documented contract assumptions, to establish work accomplishment, or to certify performance attainment shall be witnessed by the Owner and coordinated through the QCP. In order to ensure compliance with provisions of the NEC, an inspection by a licensed electrical inspector is mandatory after construction is complete. Unless otherwise identified, manufacturer recommendations shall be followed for all inspection and test procedures. Tests shall include a commissioning of the array with individual string voltage, current, and solar irradiance measured in the plane of the array and recorded. Commissioning shall be performed for the entire PV system. This data shall be used to confirm proper performance of the PV system. An acceptance test must be performed on the system once the installation is complete. This includes measuring the short circuit currents and open-circuit voltages on all source circuits while measuring irradiance and module temperature. This also includes measuring the instantaneous DC input and AC output of the system to determine its efficiency. The acceptance test form included in the appendix of this document should be completed in its entirety.Inspections/tests required in the QCP shall result in a written record of data/observations. The Contractor shall provide two (2) copies of documents containing all test reports/findings. Test results shall typically include: item/system tested, location, date of test, test parameters/measured data, state of construction completion, operating mode, Contractor Inspector/Owner witness, test equipment description and measurement technique.

(continued)

Field Training and Operation and Maintenance Manual

Operating instructions shall be posted on or near the system, and on file with facilities operation and maintenance documents. The Contractor shall prepare six (6) hardcopies and two (2) CDs containing detailed Operation and Maintenance Manual, identifying all procedures, tools, and equipment necessary to provide maintenance per manufacturer's recommendations. Manual shall include detailed wiring diagram, procedures for system start-up and shut-down, description of normal operational indicators and error indicators, troubleshooting guide describing how to identify and cure problems. The contractor shall provide a recommend list of spare parts. At the minimum a set of combiner box fuses for each array shall be provided, along with a set of replacement fuses for inverter and any other component requiring replacement fuses.

Provide training for designated personnel in the operation of the entire photovoltaic energy system, including operation and maintenance of inverter(s), transfer switches, panelboard, disconnects and other features as requested by the Owner. Instruct the Owner personnel in removal and installation of panels, including wiring and all connections. Provide the Owner with written instructions and procedures for shut down and start up activities for all components of the system. The Owner shall be permitted to video tape this training for official use.

Provide detailed Lock Out / Tag Out instructions for all equipment.

3.3 Warranty

Submit specific warranties and guarantees, final certifications and similar documents to the Contracting Officer upon substantial completion and prior to final payment. Include copies with Operation and Maintenance Manual. All warranties shall be signed by a Principal of the Contractor's firm and sealed if a corporation. The PV systems shall carry a five (5) year warranty by the installing contractor including parts and labor. The roof penetrations and roof connections shall be warranted for weather tightness for ten (10) years from the installer including parts and labor. Provide PV panel manufacturer's limited warranty guarantying a minimum performance of at least 80% of the original power for at least twenty five (25) years. Measurement made under actual installation and temperature will be normalized to standard test conditions using the temperature and coefficients published in the module specifications to measure performance. For the inverter a ten year manufacturer's warranty shall be provided.

3.4 Cleaning

Upon completion of all work under this specification, the contractor shall furnish labor, materials and incidentals to clean areas affected by the work and leave all areas in such a condition that no cleaning shall be required by the owner.

REFERENCES

Abound Solar. 2012. "Recycling." Abound.com. www.abound.com/company/recycling (accessed April 14, 2012; Abound Solar is now out of business; on March 1, 2013 www.denverpost.com/breaking news reported that First Solar had agreed to recycle Abound PV modules).

Alta Devices. 2012. "Alta Devices Solar Panel Receives NREL Verification of 23.5 percent Efficiency." news release, February 12, 2012. www.roeder-johnson.com/RJDocs/ALnrelverification0212.html (accessed April 9, 2012.

Amonix. 2005. "Amonix Is Awarded World Record Cell Efficiency." news release, June 30, 2005. amonix.com/pressreleases/amonix-awarded-world-record-cell-efficiency (accessed April 6, 2012).

ASTM. 2008. *Standard Test Methods for Electrical Performance of Non-Concentrator Terrestrial Photovoltaic Modules and Arrays.* West Conshocken, PA: American Society of Testing and Materials.

Azerbegi, R., C. Mas, R. Morris, and J. Christensen. 1999. "Determining the Best Source of Renewable Electricicy to Power a Remote Site for the National Park Service." ASME International Solar Energy Conference. Maui, HI: American Society of Mechanical Engineers.

Butti, K., John Perlin. 1980. *Golden Thread: 2500 Years of Solar Architecture and Technology.* 3rd ed. Palo Alto, CA: Cheshire Books.

Carabe, J., and J. J. Gandia. 2004. "Thin-Film-Silicon Solar Cells." *Opto-Electronics Review* 12 (1): 1–6.

Dayah, M. 1997. "Dynamic Periodic Table." (October 1). www.ptable.com (accessed April 6, 2012).

De Vos, A. 1980. "Detailed Balance Limit of the Efficiency of Tandem Solar Cells." *Journal of Applied Physics* 13 (5): 839–46.

Decher, R. 1997. *Direrct Energy Conversion: Fundamentals of Electric Power Production.* New York: Oxford University Press.

DOE EERE. 2012a. "Sunshot Initiative." (March 16). EERE.energy.gov. /www1.eere.energy.gov/solar/sunshot/vision_study.html (accessed March 27, 2012).

———. 2012b. “Sunshot Vision Study.” (February 29). Sunshot Initiative. www1.eere.energy.gov/solar/sunshot/vision_study.html (accessed April 22, 2012).

DOE OBT. 2011. “Building Energy Software Tools Directory.” (accessed March 16, 2012). Office of Building Technologies. http://apps1.eere.energy.gov/buildings/tools_directory/

DSIRE. 2011. “Database of State Incentives for Renewable Energy.” (November 27). “Hawaii Feed-in Tariff.” (November 27). www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=HI29F&re=1&ee=1 (accessed May 12, 2012).

EERE DOE. 2012. “SunShot Intiative.” (March 21). EERE.energy.gov. www1.eere.energy.gov/solar/sunshot/news_detail.html? news_id=18179 (accessed March 25, 2012).

EERE. 2011. “EnergyPlus.” (December 7). EERE.energy.gov. apps1.eere.energy.gov/buildings/energyplus/ (accessed April 27, 2012).

FEMP. 2011. “Federal Facility Reporting.” (July 1). Federal Energy Management Program. www1.eere.energy.gov/femp/regulations/facility_reporting.html (accessed May 2, 2012).

Fraas, L., and L. Partain. 2010. *Solar Cells and Their Applications*. K. Chang, ed. Hoboken, NJ: John Wiley and Sons.

Fraunhofer Institute. 2004. *Annual Report 2004 Achievements and Results*. Freiburg, Germany: Fraunhofer Institut Solare Energiesysteme.

Goodrich, A., M. Woodhouse, and T. James. 2011. *Solar PV Manufacturing Cost Model Group: Installed Solar PV System Prices*. SEGIS-ADEPT Power Electronics in Photovoltaic Systems Workshop. Arlington VA: NREL.

Hirsch, J. 2009. eQUEST. QUick Energy Simulation Tool. www.doe2.com/equest (accessed April 27, 2012).

Hoppe, H., and N. S. Sariciftci. 2004. “Organic Solar Cells: An Overview.” *Journal of Materials Research* 19 (7): 19–1945.

IEA. 2011. World Energy Outlook-Access to Electricity. World Energy Outlook 2012. www.iea.org/weo/electricity.asp (accessed March 22, 2012).

IEC. 2006. *Photovoltaic Devices*. Geneva, Switzerland: International Electrotechnical Commission.

Intel. 2008. “Intel, Samsung, TSMC Reach Agreement for 450mm Wafer Manufacturing Transition.” Spotlight News Stories, May 6. phys.org/news129301282.html (accessed April 7, 2012).

ITUSolar. 2012. “CIGS Solar Cells Reach Record Efficiency in Germany.” Itusolar.com/solar-news-r: itusolar.com/solar-news-4(Accessed April 7, 2012; more recently available at http://m.solarreport.net/7907/cigs-solar-cells-reach-record-efficiency-in-germany/).

Kim, D. S., A. M. Gabor, A. D. Yelundur, A. D. Uphadhyaya, V. Meemongkolkiat, and A. Rohatgi. 2003. “String Ribbon Silicon Solar Cells with 17.8% Efficiency.” 3rd World Conference on Photovoltaic Energy Conversion, Osaka, Japan.

King, D., J. Kratochvi, and W. Boyson. 1997. “Temperature Coefficients for PV Modules and Arrays: Measurement Methods, Difficulties and Results.” IEEE Photovoltaic Specialists Conference. Anaheim, CA: IEEE.

Luque, A., S. Hegedus 2011. *Handbook of Photovoltaic Science and Engineering*. 2nd ed. Hoboken, NJ: John Wiley and Sons.

Marion, W., S. Wilcox. 1994. *Solar Radiation Data Manual for Flat Plate and Concentrating Collectors*. Edited by M. A. Dunlap. Golden, CO: NREL.

Maycock, P. 2006. 2006 World PV Cell/Module Production: A report by PV Energy Systems Inc. Williamsburg Virginia. http://www.pvenergy.com/consulting.html

Mortensen, J. 2001. *Factors Associated with Photovoltaic System Costs*. Golden, CO: National Renewable Energy Laboratory.

Nanosolar. 2011. “Technology Nanoscience Enabled.” www.nanosolar.com/technology (accessed April 7, 2012).

NASA LARC. 2012. “Surface Meteorology and Solar Energy.” NASA.gov. https://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi (accessed March 4, 2012).

National Fire Protection Association. 2011. National Electric Code. Edited by M. Earley. Quincy, MA: National Fire Protection Association.

NIMS. 2011. “NIMS Sets a New World Record for the Highest Conversion Efficiency in Dye Sensitized Solar Cells.” news release, August 25. www.nims.go.jp/eng/news/press/2011/08/p201108250.html (accessed April 14, 2012).

Nobel Prize Foundation. 2012. Nobel Prize in Physics 1956. www.nobelprize.org/nobel_prizes/physics/laureates/1956/shockley-bio.html# (accessed May 11, 2012).

Nozik, A. 2001. “Quantum Dot Solar Cells.” NCPV Program Review Meeting. Lakewood, CO: National Center for Photovoltaics.

NREL. 2011a. “Changing System Parameters.” (June 6). *PV Watts*. www.nrel.gov/rredc/pvwatts/ (accessed April 27, 2012).

———. 2011b. “How to Change Parameters.” (June 6). *PVWatts*. www.nrel.gov/rredc/pvwatts/ (accessed April 2, 2012).

———. 2011c. “Silicon Materials and Devices R&D.” (December 20). *Photovoltaics Research*. www.nrel.gov/pv/silicon_materials_devices.html (accessed April 6, 2012).

———. 2012. “National Center for Photovoltaics.” (March 16).NREL.gov. www.nrel.gov/ncpv/ (accessed March 24, 2012.

Razykov, T. M., C. S. Ferekides, D. Morel, E. Morel, H. Ullal, and H. M. Upadhyaya. 2011. “Solar Photovoltaic Electricity: Current Status and Future Prospects.” *Solar Energy* (85): 1580–1608.

RS Means. 2011a. *Mechanical Cost Data.* 34th ed. Norwell, MA: RS Means & Co.

———. 2011b. *Green Building: Project Planning and Cost Estimating*. Kingston, MA: RS Means & Co.

S-5! 2012. “New S-5-PV Kit.” S-5.com. www.s-5.com (accessed April 22, 2012).

Santra, P. K., P. V. Kamat. 2012. “Mn-doped Quantum Dot Sensitized Solar Cells: A Strategy to Boost Efficiency over 5%.” *Journal of the American Chemical Society* 134 (5): 2508–11.

Sanyo. 2007. “HIT Solar Panels.” us.sanyo.com. us.sanyo.com/Dynamic/customPages/docs/solarPower_HIT_Solar_Power_10-15-07.pdf (Accessed April 7, 2012).

SBIC. 2012. “Energy10.” Sustainable Buildings Industry Council. www.sbicouncil.org. (accessed March 16, 2012; no longer posted; now refer to www.nibs.org/?page=sbic)

Sharp. 2009. “Sharp Develops Solar Cell with World’s Highest Conversion Efficiency of 35.8%.” news release, October 22. sharp-world.com/corporate/news/091022.html (accessed April 7, 2012).

Sharp, T. 1994. *Energy Benchmarking in Commercial Office Buildings.* Oak Ridge,TN: Oak Ridge National Laboratory.

Shockley, W., and H. Queisser, H. 1961. “Detailed Balance Limit of Efficiency of p-n Junction Solar Cells.” *Journal of Applied Physics* 32 (3): 510–19.

Solar Junction. 2011. “Products.” Solar Junction. www.sj-solar.com/products/ (accessed April 9, 2012).

Solarbuzz. 2012. “Module Pricing.” www.solarbuzz.com/facts-and-figures/retail-price-environment/module-prices. (accessed April 22, 2012).

SolarFrameworks. 2012. “Solar Frameworks Innovative Systems.” BIPV Coolply. www.solarframeworks.com (accessed April 27, 2012, no longer available)

SolarIntegrated. 2011. “Product Solutions.” www.solarintegrated.com (accessed April 22, 2012, no longer available).

SunPower Corp. 2012. “Solar Power Plant Products and Services.” Sunpowecorp.com us.sunpowercorp.com/power-plant/products-services/ (accessed June 6, 2012).

Tamizh Mani, G., J. Kuitche, and A. Mikonowicz2012. “Nameplate, Datasheet, and Sampling Requirements of Photovoltaic Modules.” www.solarabcs.org/about/publications/reports/nameplate/pdfs/Nameplate_fullreport.pdf (accessed April 15, 2012).

Tucson Electric Power. 2007. “PV Data.” *Progress in Photovoltaics: Research and Applications*, 16: 249–59.

Uni-Solar. 2010. “UNI-SOLAR Unveils Technology Roadmap for Conversion Efficiency of 12 Percent and Cost-Per-Watt of Less Than One Dollar By 2012.” (June 1). www.uni-solar.com/2010/06/uni-solar-unveils-technology-roadmap-for-conversion-efficiency-of-12-percent-and-cost-per-watt-of-less-than-one-dollar-by-2012/ (accessed April 7, 2012, no longer available).

———. 2011. “Uni-Solar Breaks Thin-Film Solar Efficiency Record.” (July 12). www.uni-solar.com/2011/07/united-solar-reaches-16-3-efficiency-with-nano-crystalline-technology/ (accessed April 7, 2012, no longer available).

US Energy Information Administration (EIA). 2010. “Table 3.15 Shipments of Complete Photovoltaic Module Systems.” *Solar Photovoltaic Cell/Module Manufacturing Activities.* http://www.eia.gov/cneaf/solar.renewables/page/solarphotv/table3_15.html (accessed April 25, 2012

———. 2011a. *Annual Energy Review*. Table 10.8: Photovoltaic Cell and Module Shipments by Type, Trade, and Prices, 1982–2009. Available at www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb1008 (accessed April 23, 2012).

———. 2011b. *Solar Photovoltaic Cell/Module Manufacturing Activities.* US Energy Information Administration. www.eia.gov/cneaf/solar.renewables/page/solarphotov/solarpv.html (accessed March 25, 2012).

US EIA. 2012. “Electricity Prices by State.” *Electricity Data.* 205.254.135.7/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_b (accessed May 12, 2012).

USGS. 2002. *Mineral Commodity Profiles: Cadmium*. US Department of the Interior. Reston, VA: US Geologic Survey.

von Roedern, B., H. Ullal 2007. “Thin Film CIGS and CdTe Photovoltaic Technologies: Commercialization, Critical Issues, and Applications.” Twenty-second European Photovoltaic Solar Energy Conference and Exposition. Milan, Italy: NREL.

Walker, A., J. Christensen, G. Barkerand L. Rawlings, L. 2002. “Short-Term Measurement of a Photovoltaic-Fuel Cell Remote Hybrid Power System at Golden Gate National Recreation Area.” ASME Solar 2002 Sunrise on the Reliable Energy Economy. Reno, NV: American Society of Mechanical Engineers.

Wiles, J. 2010. *Photovoltaic Systems and the National Electric Code: Suggested Practices.* Las Cruces, NM: Southwest Technology Development Institute, New Mexico State University.

Wiser, R., G. Barbose, C. Peterman, and N. Darghouth. 2009. *Tracking the Sun II: The Installed Cost of Photovoltaics in the U.S. from 1998–2008*. A report by Lawrence Berkeley National Laboratory. Berkeley, CA: LBNL. Available at http://eetd.lbl.gov/ea/emp/reports/lbnl-2674e.pdf (accessed March 2013).

Zwiebel, K. 2010. "The Impact of Tellurium Supply on Cadmium Telluride Photovoltaics." *Science* 328 (5979): 699–701.

4

Solar Water Heating

As a teacher in rural Nepal I took a shower once a week whether I needed it or not. I'm sure it would have been better for everyone involved if I bathed more often, but the water was unbearably cold and it was impractical to heat it with firewood. Simple unpressurized solar water heaters are making a difference in the lives of rural people all over Asia, and solar heating integrated into a building plumbing system is common in many countries.

Solar water heating systems are simple extensions to a building's hot water plumbing system that have components and controls similar to those of a hydronic (hot water) heating system, which is a very common type of heating system in buildings. In addition to the conventional fuel-fired water heater, they use solar collectors as a source of heat. Since the solar heat is intermittent, a storage tank stores the solar heat for when it is needed. The optimal approach is to meet around two-thirds or three-quarters of the hot water needs with solar and to rely on the conventional heating system to provide the balance. It is usually not cost-effective to try to meet 100 percent of the load with solar because to do so requires a very large storage tank and very large solar collector array, the efficiency of the system diminishes as the load is satisfied, and more operational problems (overheating) occur in oversized systems. However, where conventional fuel is expensive or unavailable, buildings do rely on solar as their only source of hot water, including many buildings in developing countries and also some projects in the US such as some laundry and shower facilities at a campground in Oklahoma. "Net-zero" buildings (buildings that are seeking a fossil energy use of zero), would also involve a system that strives to provide all of the hot water from solar.

Different types of solar collectors have different constructions depending on the required temperature of the heated water. Unglazed collectors have a black surface to intercept solar radiation and flow passages to contain the fluid to be heated and are often made of plastic. Unglazed collectors are used to warm swimming pool water. Glazed flat-plate collectors use glass covers and insulated enclosures in order to achieve a higher temperature needed for most other hot water uses, such as domestic use. With the superior insulation of a vacuum, evacuated-tube solar collectors perform well at temperatures equal to and higher than glazed flat-plate collectors. Complete systems include solar collectors, storage tanks, heat exchangers, and other components typical of a hydronic heating system such as valves, expansion tank, pumps, and controls.

Solar water heating systems perform best when preheating cold incoming water, but it is also possible to reheat recirculated hot water if a well-insulated collector is used. Solar water heating is most cost-effective in the following applications:

- When reducing the consumption of expensive fuels such as propane or electricity to heat water.
- When serving a steady load that uses hot water 12 months per year and 7 days per week.

A sunny climate helps, but solar heating systems have been found to make some contribution at all locations on the globe, even locations in cloudy climates and high latitudes. Examples of the best applications include domestic water heating; pool heating; laundries; cafeterias; prisons; hospitals, and industrial processes.

People have always noticed the warming power of the sun, and I'm sure that as soon as glass was invented, people became aware of its ability to trap solar heat. The first descriptions of a solar collector constructed as a box, with a black absorber surface and a glass cover, date back to the eighteenth century. In a good history of the solar industry, Ken Butti and John Perlin describe how Samuel Pierpont Langley used the temperature of such a box to measure the intensity of solar radiation on an 1881 mountaintop expedition (Butti & Perlin 1980). A unit of measurement for solar radiation, the Langley, or 1 cal/cm^2, is named in his honor. The first commercially marketed solar collector was patented by Clarence Kemp in 1891 and marketed as the “Climax” water heater. It consisted of an iron tank painted black under a glass cover in a wooden box insulted with felt. Other than using different materials for the tanks and insulation, it looked very much like a type of water heater available today. In 1909, William Bailey patented a system, called the “Day and Night,” which separated the solar collector from a well-insulated tank, and which used thermosyphon action to circulate water between the collector and the tank when solar heat was available. A well-insulated storage tank, and the practice of including supplementary heat from a gas-fired heater, allowed systems to provide hot water at any time, a new and valued convenience. Use of a nonfreezing fluid in the collector allowed the market to expand further, and in 1920, the company sold 1,000 of these heaters, mainly in Southern California. The same book (Butti and Perlin 1980) reports that in 1941, the sale of solar water heaters exceeded the sale of conventional heaters by two to one in Miami, Florida. The equation still used to calculate the efficiency of a solar collector was published by Hottel in 1942 (Hottel 1942). However, as electricity and natural gas utilities expanded, consumers chose future monthly bills over a high initial cost, and many of the solar companies in the US converted what they knew about insulated tanks to the manufacture of gas water heaters. It’s interesting that solar manufactures evolved into gas-fired heaters rather than vice-versa. In other countries, however, especially Israel in the 1950s and Australia and Japan in the 1960s, the solar water heater industry continued to grow. In the 1980s, researchers at Qing Hua University in Beijing, China developed the evacuated glass tube technology that would come to lead the Chinese market.

Interest in solar water heating in the US increased when energy became an important economic, environmental and political issue in 1973. Dr. George Lof, who built the first liquid-heated solar house at Massachusetts Institute of Technology in 1938, started a company to sell liquid-heating solar systems in 1974 and founded the Solar Energy Applications Laboratory at Colorado State University. There was a lot of government-sponsored research published in the late 1970s and early 1980s. Bill Beckman, John Duffie, and Sandy Klein at University of Wisconsin, Madison, developed the a computer program to simulate solar water heater performance called TRNSYS and the related FCHART and wrote the book *Solar Energy Thermal Processes,* published by Wiley Interscience in 1974. Subsequent versions of the book remain an authoritative reference (Beckman and Duffie 2006). United States president Jimmy Carter inaugurated the Solar Energy Research Institute (now the National Renewable Energy Laboratory) in 1979. The U.S. solar thermal market increased dramatically in the years that federal tax credits were in effect from 1981 to 1986. When the tax breaks expired in 1986, so did many of the companies, but those that survived the years from 1986 to 2005 without tax incentives improved the technology and economic value of the technology. The 30 percent U.S. Federal Investment Tax Credit available since 2005 was extended for residential and commercial solar water heating systems through 2016, evidence of public policy in support of solar water heating.

By 2009 over 244 million m^2 (2.6 billion ft^2) of solar water heating collectors had been installed worldwide. China is by far the largest and fastest-growing market for solar water heating with over half the installed capacity and some 80 percent of the new installations. The Chinese market is mainly evacuated-tube technology for domestic water heating. There are perhaps thousands of solar water heating companies in China employing tens of thousands of people. Himin Group, based in eastern China’s Shangdong province, is the largest manufacturer in China and in the world. Growth in China may be expected to continue due to a large as-of-yet-unmet demand, a large population, and the ability of the industry to deliver very effective technology at a large scale and a low cost. On a per-capita basis, leading users of solar water heating are Cyprus and Israel, where, based on the view from a hotel roof, all the buildings have solar hot water. Turkey, Greece, and Australia also represent large markets due to large populations and favorable conditions (IEA 2009).

As illustrated in Figure 4-1, the US is also a large market, but most of these are unglazed collectors for heating residential

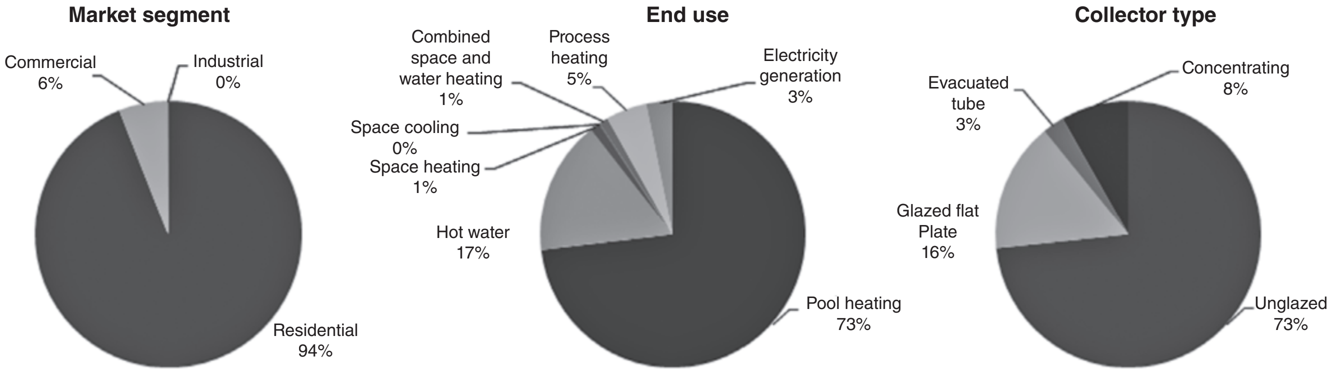

Figure 4-1. Statistics reported by EIA show that the largest segment of the US market is heating residential swimming pools with unglazed collectors. Breakdown is by square footage, total square footage = 1.135 million m^2 (12,221 thousand ft^2) per year. [Figure Charts of US solar hot water market characteristics. (Figure by the author, using data from EIA (Wong 2011)

swimming pools in Florida and California. This market has leveled off in recent years, perhaps due to general real-estate trends. Domestic water heating in Hawaii is also an important market. In 2011, the US solar industry was described as 88 manufacturing companies employing over 1,300 persons and shipping over 10 million square feet of solar collectors (Wong 2011). Examples of US manufacturing companies include Heliodyne, SunEarth, and FAFCO in California and Alternate Energy Technologies in Florida. That the US market is dominated by unglazed solar collectors for residential swimming pools indicates the untapped potential for other types of buildings. I believe that there is a lot of business opportunity for mechanical, electrical, and plumbing (MEP) firms in the US to include solar water heating in their designs.

Solar water heating technology has also been applied to many industrial processes and also to thermally driven cooling cycles. Solar heating technology has also been used for space heating, but because the space heating load is a maximum precisely when the solar radiation is a minimum, such systems are technically challenging and cost-effective only under unusual circumstances. In 2008 and 2009, out of 1,771,000 ft^2 of flat-plate solar collectors sold in the US, only 70,000 ft^2 was used in space heating systems and 100,000 ft^2 was used in systems that provide both hot water and space heating (Wong 2011). This author has operated such a combined (water heating and space heating) system on a property since 1991, and has yet to see a significant contribution toward space heating, although hot water is more than sufficient. For space heating superinsulation and passive solar architecture strategies such as those described in Chapter 6 are recommended. Water heating is a load that persists all year long and provides a good match to the solar resource.

Interview with Solar Pioneer Bob Hassett

Bob Hassett (see Figure 4-2) is a registered professional engineer with over 37 years of experience. He completed his BS and MS in mechanical engineering at the University of Maryland and cofounded Applied Solar Technologies, Inc. He recently retired after 30 years with the US Department of Energy Office of Energy Efficiency and Renewable Energy as manager of the Solar Heating and Cooling and the Building Integrated PV programs, overseeing research, development, and deployment activities for solar hot water. He serves on the board of directors of the Solar Rating & Certification Corporation (SRCC), and has extensive involvement with Solar Energy Industries Association (SEIA), the Interstate Renewable Energy Council (IREC), the Institute for Sustained Power Quality (ISPQ), the North American Board for Certified Energy Practitioners (NABCEP), the Utility Solar Water Heating Initiative (USH2O), and the Solar Workforce Development Program. He also served as the US delegate to the International Energy Agency (IEA) Solar Heating and Cooling and PV Power Systems Executive Committee, transforming US involvement from that of passive observer to proactive and influential partner.

Figure 4-2. Robert Hassett cuts the ribbon at the opening celebration of a new Hot Water Systems Laboratory at Florida Solar Energy Center. He's joined by (from left to right) Danny Parker, Subrato Chandra, and Carlos Colon. (Photo courtesy of Florida Solar Energy Center)

As leader of the US Department of Energy research program from 1980 to 2011, what are some accomplishments in solar water heating that you are most proud of?

Arriving at the US Department of Energy (DOE) in 1980, it was a time of great promise and expectations with growing funding initiatives for residential, commercial, and federal demonstrations of solar water heating. At that time, it was the widespread belief that the technology was mature and that a large number of demonstrations would provide economies of scale, reduce cost, and develop a base market for the US solar industry. The DOE SHC Program also initiated the National Solar Data Network (NSDN) and the Reliability & Maintainability (R&M) programs to monitor their thermal and operational performance in order to validate the presumed viability of solar hot water for consumers. Instead, the NSDN and R&M Programs documented widespread failures, costly repairs, and early abandonment of way too many of these SHC systems. The legacy that I am most proud of is the response of redirecting a major part of the program to refocus efforts to identify, understand, and rectify technical failures. Significant issues remained in the areas of poor system design, installation, and proper maintenance of SHC systems. I'm most proud of supporting independent entities such as SRCC, which certifies solar thermal products; NABCEP, which certifies installers; ISPQ, which certifies trainers and training programs; and the Weatherization Assistance Program (WAP), which establishes a network of training institutions. I initiated a new IEA task on globally harmonized rating and certification procedures within the IEA SHC Implementing Agreement, eliminating a huge barrier to the commercialization of SHC.

I was frustrated by the huge difference in the US market and that of other countries. For example, the EU alone has roughly the same population, land area, and building stock as the US with a significantly lower solar resource. Yet, the EU market is currently estimated to be 750,000 to 1 million SHC installations per year, compared to an estimate of 20 to 30 thousand installations per year in the US. The US market is largely viewed by foreign suppliers as a vastly undeveloped market with great potential, and foreign suppliers are applying for SRCC certification in order to qualify for financial incentives at the federal, state and local levels within the US. This created a backlog of applications to SRCC which adversely affects US and foreign suppliers equally. Once again, I reallocated significant DOE SHC resources to help SRCC establish multiple accredited testing laboratories in several countries and sufficient internal staff to process applications in an acceptable timeframe.

Are there new developments coming or is this technology fully mature in your opinion?

I'm very proud of new, innovative concepts that I was involved in such as transpired solar collectors, PV/thermal hybrid collectors, solar desiccant systems, and low-cost polymeric collectors. I can't help but wonder what amazing accomplishments lie ahead for the use of new materials, manufacturing processes, and design concepts. This industry is constantly striving for increased performance, reliability, durability, manufacturability, and cost-effectiveness. As much as the industry and SHC products have matured, they have yet to achieve an "appliance-like image" of the more conventional products that the end-user demands. (An example of success at this is the heat pump water heater, HPWH). Of course, the strategic long-range promise for SHC is its reliance on the infinitely available and secure solar energy resource versus the finite and insecure availability of fossil fuel resources. However, the high up-front cost of solar presents a significant barrier to the widespread utilization of renewable energy in general and SHC in particular.

Since retiring from DOE, you've been elected to the board of the Solar Rating and Certification Corporation (SRCC). What are the pressing priorities regarding codes and standards related to solar water heating?

Establishment of SRCC is one of the most important accomplishments for the solar industry in the past 30-plus years. All through the 1980s and into the 1990s, SRCC was a very contentious issue within the ranks of many in the solar industry, but it is my firm belief that the industry owes its current and eventual success to the continued support of the SRCC. In short, the SRCC provides the requisite quality assurance to the industry, stakeholders, consumers, and the local, state, and federal regulatory bodies that is essential for the widespread acceptance and commercialization of solar heating technologies. A challenge for SRCC is to develop new ratings and test procedures for industry's new innovative product lines without delaying new product introduction. SRCC must continue to bring together the certification bodies for Europe, North America, Australia, and China to harmonize testing and certification procedures. This effort lays the potential foundation towards global consistency and implementation in the standards for testing and certification across international borders which would reduce barriers and costs. We also hope to institutionalize a definitive link between solar products and solar installer training. Collectively these efforts provide a comprehensive approach towards increased quality assurance for solar products and installations. I consider these to be pressing priorities which I hope to institutionalize within these various entities.

DIFFERENT TYPES OF WATER-HEATING SOLAR COLLECTORS

The modular unit of a solar water heating system is called a "solar collector." There is a wide variety of products offered on the market. Three of the most common types to be found on buildings are: unglazed; glazed flat-plate; and evacuated tube solar collectors. Parabolic trough collectors use tracking mounts and focusing mirrors with an evacuated-tube absorber assembly, and are mounted on the ground. Integrated-collector-storage (ICS) systems incorporate water storage volume within the solar collector box. All-plastic collectors are available, but most involve aluminum frames, copper tubes and absorbers, and tempered glass covers.

Unglazed Solar Collectors

Sunlight is distributed, so a large aperture of surface area with a high absorptivity is used to intercept the required amount of solar energy. The surface must also form a heat exchanger with the fluid to be heated. The most inexpensive way to do both has been to extrude a sheet of plastic with the flow passages molded into it, creating what is known as an "unglazed collector." An example of such a low-temperature unglazed solar collector is shown in Figure 4-3.

Although unglazed collectors have been constructed out of painted metal, materials used currently include polypropylene, polyethylene, and polyolefin plastics. Since these polymer materials are subject to ultraviolet degradation, they are treated with

Figure 4-3. An unglazed solar collector for heating swimming pool water is made of flow passages extruded in plastic, as shown in this close-up photograph. (Photo by the author)

UV stabilizers and antioxidants to extend their useful life to well beyond the 10-year warranty typical of such products. Carbon black is added to the plastic and contributes to the permanent color and UV protection. The material is a black color to absorb as much solar radiation as possible. The black polyolefin used by FAFCO in manufacture of their unglazed solar collector is reported to have an absorptivity of 0.96 in the product literature (FAFCO 2010). Since the absorbing surface is exposed to the elements, the fragile "selective" surface treatments used in glazed collectors are not provided for unglazed collectors. This is of little consequence. Because of the low-temperature operation, radiant heat loss is not excessive. Unglazed collectors have no cover glass to reduce solar radiation by reflecting or absorbing it, so they have a higher optical efficiency (intercept more incoming solar radiation) than glazed collectors.

For low-temperature applications, such as swimming pool heating, insulating the absorber would not be cost-effective and may even be counterproductive if the ambient temperature is warmer than the pool water. But at higher water temperatures heat loss from the unglazed collector is excessive. With no flow through it, an unglazed collector may reach a temperature of 25C (50F) above ambient temperature in full sun. But as we take heat from it, the temperature drops, so unglazed collectors are only used for heating water to about 10C (20F) above ambient temperature.

The plastic unglazed collectors have no rigid frames and must be supported throughout their area. They are often laid flush on a roof and held in place by straps and attachment points.

Manufacturers of unglazed solar collectors include FAFCO in California,[1] Uma Polysolutions in India,[2] Solar Hydronics Corp. in Florida,[3] and Aquatherm Industries Inc. in New Jersey (Aquatherm 2009), to name a few.

Definitions

Optical Properties of Materials

ASTM E1175-87 (2009) *Standard Test Method for Determining Solar Reflectance, Transmittance and Absorptance of Materials Using a Large Diameter Integrating Sphere* describes a method to ascertain the optical properties of materials as related to solar wavelengths.

Absorptivity, α

Absorptivity is defined as the fraction of solar radiation incident on a surface that is not reflected from nor transmitted through and thus is captured and converted to heat within the absorbing surface, and is given the symbol α. A perfectly absorbing surface would appear black because no colors of light would be reflected from it. Absorption of light is described by the theory of "disruptive optical interference," and often depends on thin layers to match the wavelength of incoming light. Thus, absorptivity of a surface depends on wavelength of the incident light, and for solar water heating collectors a high absorptivity in the solar spectrum is desirable. A very comprehensive survey of solar absorptivity of common materials was conducted in the 1970s by Honeywell for the federal government, and since then new surface treatment technologies have been developed especially to absorb the solar wavelengths. Examples of solar absorptivity for materials that one might consider for a solar collector are listed in Table 4-1.

TABLE 4-1. SOLAR ABSORPTIVITY OF SELECTED MATERIALS (SOLAR MIRROR, 2012)

Absorber surface	Solar Absorptivity
Aluminum, anodized	0.15
Black paint	0.95
Blackened nickel	0.92
Black polyolefin plastic	0.96
Black polyethylene plastic	0.94

Transmissivity, τ

Transmissivity is defined as the fraction of incident solar radiation that passes through the cover glass of a solar collector,

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[1] www.fafco.com (accessed March 2013).

[2] www.solarpoolpanel.com/quality.html (accessed March 2013).

[3] www.nuvissolar.com/aboutSHC.html (accessed March 2013).

and is given the symbol τ. Transmissivity is reduced by reflection off the glass and absorption within the thickness of the glass. Absorption as the radiation travels through the thickness of the glass is an exponential decay based on a parameter called the “extinction coefficient.” Glass used in solar collectors uses chemistry to have a low extinction coefficient in the solar spectrum, such as a low iron content. Absorption depends on the thickness of glass that the light must travel through, which is proportional to the cosine of the incident angle. The glass must be tempered to provide adequate strength and resistance to hail and other impacts. The transmissivity of glass and polycarbonate products is listed in Table 4-2 (Both 2007). Some other plastics used in building or greenhouse glazings are not suitable for solar thermal collectors because they melt under the high temperatures.

TABLE 4-2. TRANSMISSIVITY OF GLASS AND POLYCARBONATE GLAZING MATERIALS

Material	Transmissivity
Glass	0.90
Polycarbonate	0.87

Reflectivity, ρ

Reflectivity, ρ, is the fraction of incident solar radiation that is reflected back off the surface, and thus not transmitted or not absorbed. Reflectivity depends on the index of refraction of the glass and the incident angle at which the radiation strikes the surface of the glass according to equations named after Snell and Fresnel in the field of optics. Some collector manufacturers use textured glass to decrease reflection when the sunlight is not perpendicular to the glass. Etching the surface of the glass with acid reduces the reflectivity from about 8 to 3 percent, and is constant over wider incidence angles. An antireflective coating consisting of a layer of glass with a low refractive index and a thickness equal to one-quarter of the wavelength of the incident light is applied to the outer surface of the glass. At this thickness, light reflected from the top and bottom of the coating are 180 degrees out of phase and reflection is canceled out. Such a coating may be created by dipping the glass into a solution saturated with silica, and drawing it out at just the right speed. Such an antireflective coating can reduce the reflectivity of glass from 8 percent to 2 percent. The very thin metallic antireflective coatings used for camera optics have been too expensive for solar collector use.

Relationship between Optical Properties

All of the incident light must be absorbed by the surface, reflected from it, or transmitted through it. So for any surface the relationship holds:

$$\alpha + \tau + \rho = 1 \tag{4-1}$$

For opaque absorber surfaces the transmissivity is zero and the goal is to maximize absorptivity by minimizing reflection. For transparent cover glazing the objective is to minimize reflection off the surface of the glass and absorption in the thickness of the glass in order to maximize transmissivity. Some fraction, (1-α), of the radiation making it through the cover glass is reflected back up off the absorber surface. This is reflected back down toward the absorber again by the underside of the glass. So the effective transmittance-absorptance product is about 1 percent higher than simply multiplying the two together.

$$\tau\alpha_{\text{effective}} = \frac{\tau\alpha}{1-(1-\alpha)\rho} \tag{4-2}$$

Where ρ in this equation is the reflectivity of the underside of the glass. In this book we will use the results of testing manufactured solar collector products, rather than calculating details of performance internal to the collector. Since in this approach transmissivity and absorptance only appear as the transmittance-absorptance product, we drop the “effective” subscript.

Glazed Flat-Plate Solar Collectors

In order to achieve higher temperatures than the unglazed collector is capable of, the absorber of a glazed flat-plate solar collector is a made of very thin metal (usually copper) instead of plastic, and is encased in a well-insulated enclosure with one or two sheets of cover glass. The copper absorber sheet is treated with a “selective” surface on the side facing the sun and shiny untreated metal on the other side. The thin copper absorber sheet is welded to provide good conducting connection to copper riser tubes in which the fluid to be heated is circulated. The riser tubes are soldered into holes in manifolds at the inlet and outlet of the solar collector. The sides and back of this absorber sheet/tube assembly is insulated with fiberglass, rigid sheets of polyisocyanurate, or both. Such an assembly is shown in Figure 4-4. This level of insulation allows the solar collector to provide useful heat up to, say, 50 C (129 F) above ambient temperature. A sheet of metal, plastic, or fiberglass usually protects the insulation on the back side of the solar collector.

There are many manufacturers of glazed flat-plate solar collectors, including US companies Alternate Energy Technologies, Heliodyne, Rheem, Lochinvar, and Sun Earth; German companies Schuco, Stiebel Eltron and Veissmann; Spanish company Zueco; Chromagen in Israel; Caleffi in Italy; Papaemmanouel in Greece; and Sinoyin Solares in China.

Evacuated-tube Solar Collectors

An evacuated-tube solar collector consists of an absorber surface that is suspended inside a glass tube from which the air has been evacuated. Sunlight passes through the vacuum, but once the radiation is absorbed, there is no air to form conductive or convective heat loss. Thus evacuated-tube collectors have less heat loss than other types of collectors and can deliver heat at

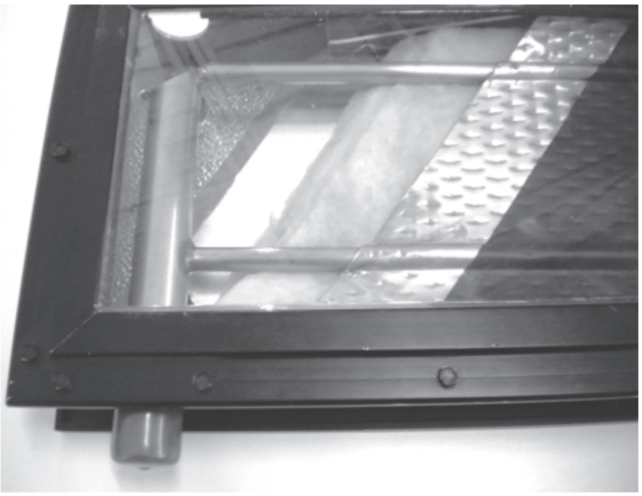

Figure 4-4. A glazed flat-plate solar liquid-heating collector includes a cover glass, absorber plate with selective surface, riser tubes, manifold and insulation, as shown in this cut-away sample. (Photo by the author)

temperatures higher than 50° C (129°F) above ambient temperature. One of first successful evacuated-tube products was by Themomax, an English company, which used a heat pipe assembly to deliver the heat from the inside of the tube to the header. What was different about the Thermomax collector is that it was designed by an aerospace engineer, rather than evolved from plumbing practice as did flat-plate collectors. As a result, it was made of lightweight yet strong materials and was very efficient. Advanced rubber materials formed the seal between the glass tube and the metal heat pipe. A variation utilized by Chinese manufacturers welds two glass tubes together and evacuates the space between the two. This avoids the glass to metal connection. Both the glass-to-glass and condenser bulb arrangements are shown Figure 4-5.

Evacuated-tube solar collectors are the most common type manufactured in China. Manufactures in China include Himin Solar Co. in Shandong, Sunda Solar Energy Technology Co. in Beijing, Haining Jixiang in Zhenjiang, Changzhou Erjin Co.in Jiangsu, and Apricus. Solar Panels Plus manufactures evacuated-tube solar collectors using Chinese technology in Ohio. Viessmann, a German company, also offers an evacuated-tube solar collector.

Figure 4-5. An evacuated-tube solar collector consists of two glass tubes welded together or an evacuated glass tube enclosing the absorber plate and a heat pipe assembly to remove the heat, as shown in this close-up photograph of the heat-pipe condenser bulb. (Photo by the author)

CONCEPT

Pressurized versus Unpressurized Collectors

In China, there are a lot of suppliers that manufacture simple solar collectors that are not built to contain high water pressure and fewer that manufacture pressurized collectors. Unpressurized systems heat tanks that are open to the atmosphere and are the most common type of system in rural China. Swimming-pool systems have a low pressure, but solar collector water heating systems in most other situations do operate with an internal working pressure that depends on the type of system schematic and depends also on if the strategy to suppress boiling in the collector includes pressurization. Be sure the collector you purchase meets the pressure requirements of your system.

Interview with Huang Ming, Founder of Himin Solar, China

Huang Ming, perhaps the world's first solar billionaire, has been described as an inventor, an entrepreneur, and a visionary. His goal as founder of Himin Solar Co. is to make solar systems popular in China and to make sure all heating and cooling in China is done with solar energy. Huang Ming believes that business has a lot to offer and to contribute to the transition to a sustainable future. Huang Ming served in the People's Congress, where he sponsored a 2006 Renewable Energy Law. Recently, he has been tirelessly promoting solar worldwide and has been recognized by the UN and received several international awards.

Himin Solar produces 2 million m^2 (21 million ft^2) of solar water heating collectors every year. In total by 2011, it has produced 10 million m^2 (107 million ft^2). Help us understand the magnitude of those numbers…what is the impact?

Actually, in the 10 years that Huang Ming Inc. has been in business, the cumulative production of solar collectors has reached

20 million square meters. This is the energy-saving equivalent of more than 4,600 tons of standard coal *per day*, equivalent to the annual output of 10 medium-sized coal mines to reduce the corresponding pollutant emissions of nearly 4,000 million tons [of CO_2] per year. The goal is to produce more than 300 million square meters, equivalent to the sum of the EU, even more than twice that of North America, and to promote the rate of more than 70 percent per year increase, to achieve good social benefits.

Before the protection of the environment, business always acted as the role of the traitor, but Huang Ming Inc. created the solar energy sustainable development model and has opened up a “Business and the Environment, Harmony Road” to achieve win-win between the environment and industry. Huang Ming completed ten years of time in western countries which have taken 60 to 100 years to complete the road of industrialization, in order to find a solution to the world of alternative energy that has become the benchmark of the world for renewable energy and sustainable development.

Government and enterprises must first determine whether energy saving and environmental protection or new energy industry development is dominant. Government and enterprises should not think that the government is pushing and the enterprise is in the pull. There is economic opportunity in responsibility. Companies should consider how much opportunity there is. There are many opportunities. In order to make it more likely that a company’s leadership position is greater, enterprises should grab the opportunity to take responsibility. But there is a problem: businesses can choose a big or small role.

Here I am not representing myself personally or my business, but should be representative of the economic sector, why do you say, for example, energy conservation?...or is this a matter of climate change commitment, or the Kyoto Protocol, or matters of government, or is it a matter of energy-saving companies? Rather, it is the responsibility of the entire community, the world of things. If we really want to do this job well, a number of governments alone, a few energy saving enterprises alone, are not enough.

I wish the US solar energy utilization was as much as China’s. Do you have any suggestions for the utilization of solar energy for the US?

The Obama administration would also like to accelerate the pace of action, the development of effective policy, but the next administration cannot achieve goals alone, and also needs Congress to push through laws for long-term renewable energy. The most effective way is to get people aware of all actions of leadership, and should rely more on cities, states, and sub-national level. Regulations can help to encourage the implementation of renewables, but the people have to act as well.

In the field of renewable energy promotion and energy-saving products, there are three success stories: one in Germany, they introduced a feed-in tariff policy; the second the use of solar thermal power plants in the California desert is a good example; the third example is the green grass-roots reform of China (grassroots level). The Chinese government only provides you with the foundation or platform to promote the development of grassroots or private industry and the promotion of solar water heaters, for example, in the whole of China. This difference in the national government, provincial, state, local governments and civil society, business and economic circles on three levels sets an example for the future of renewable energy promotion.

We understand that you are involved in other areas, including windows and doors, solar power plant development, and community building. How are these areas integrated together?

We use a “Microemissions World” strategy to the perfect combination. After the Copenhagen summit, energy conservation has become a global hot topic, but mostly in a reduced stage of consciousness. With the increasing global energy conservation requirements, simple energy-saving products or technology has been difficult to meet the needs of development. In September 2010, during the Fourth World Conference in Sun City, I first proposed the strategy of Microemissions World; its thrust is large area replication through practice and improvement. The future template is a global push forward to jointly cope with two major global problems of energy and the environment. The Microemissions Earth strategy is to join hands around the world to build green, sustainable cities, including microemissions rural, microemissions community, microemissions factories, and microemissions transportation. Comprehensive utilization, including solar and other clean energy technologies, reduces personal and organizational production of waste (carbon dioxide, sulfur dioxide, sewage and contaminated water, solid waste (dust, garbage, etc.) and even achieve zero emissions.

The basic points of the strategy are known as the “future of the world of the Valley”—the practice of Huang Ming Sun Valley to improve microemission integration of urban and rural areas. Huang launched “Ark engineering” with Huang Ming Sun Valley, our headquarters located in Dezhou, Shandong, as a starting point. Sun Valley lays out a “micromission earth” strategy implementation road map; 2014 is the demonstration phase of the Ark project. Each city of the country will … build a microemissions demonstration area, that is a future Ark. In the popular stage in 2020, the world’s major cities will begin to build the next-generation Ark; and by 2060 Ark Fleet will have entered into a mature and upgrade phase, the entire planet to fight for the real green “Microemissions Earth.”

Templates number through the full application of solar and other clean energy technologies to achieve a full range of live entertainment, transportation, and tourism, and industrial production, all with microemissions. The term “PaD” means Packaged Design, incorporating microemissions wisdom of integration and solutions. ME-PaD is a set of microemissions integrated solutions, intelligent energy management

(continued)

platform, and presents the future of humanity a new way of life. It focuses on the realization of human self-help, follow the function of human nature, ecological clean, beautiful and harmonious principle, provides the world with a new way of life for the user to build green, smart, stylish and comfortable living environment. Town-PaD is solutions for intelligent integration of systems of town and town-level microemission energy planning/design, industrial and agricultural circular economy, energy-efficient building design, green road and other solutions, solar bus/light rail/ferry boats to replace the traditional means of transportation; application of solar energy (high temperature, photovoltaic, wind, biogas power generation) in office buildings, residential areas, hotels, parks, and so the use of solar heating and cooling, energy storage, energy-saving windows and doors, and many other leading energy-saving technologies. Home PaD is ranked smart home integration and solutions and Campus PaD is design, planning construction to install low-carbon microemissions student apartments, school buildings, libraries, laboratories, and zero-energy stadium (gymnasium), and teachers' living quarters (districts), and to beautify the campus [with] photovoltaic lighting art, recycling of resources, and green restaurants. Port PaD is related to airports and ports, and Fac PaD relates to factories and includes plant energy conservation, heating and cooling power; textile printing and dyeing; brewing roasted tea and flue-cured tobacco; large-scale industrial heat (water, air, steam, etc.); and factory integrated conservation and clean-energy solutions. Core technologies and products include cloud computing, the Internet, and a central processing system, which is visible and controllable; smart thermostats, solar air conditioning, solar heating, energy-saving doors and windows, photovoltaic and BIPV, the new wind sculpture, ground source heat pumps, rainwater harvesting, and the integrated use of technology to ensure the quality of life and taste.

We built Wei City to explore a combination of solar energy and green buildings, and a variety of binding modes and the way they operate. A comprehensive system of energy optimization is demonstrated through the use of exterior insulation and efficient building envelope to make the building energy-efficiency goals reach more than 70 percent. A centralized solar hot water system provides 70 percent savings and individual home systems provide more than 40 percent of the water heating needs. Solar provides 90 percent of the air-conditioning energy consumption of residential houses, and the grid system of efficient electricity distribution saves 4 percent of the electricity. All windows and doors are energy-saving (glass U-value of 1.1W/m/K, whole window U-value of 1.3W/m/K). The building with an area of 40,000 square meters is a model of the modern green energy-saving residential building.

Wei City Sculpture Park uses my company's R&D and production to demonstrate a variety of sculptures, landscape lights, light sources using LEDs, energy-saving lamps, high luminous efficiency, and low power consumption. The generating capacity of the sculpture park is 30,000 kWh per year of electricity, and corresponds to savings of about 10 tons of standard coal, 39.6 tons of carbon dioxide emissions per year. Therefore, Wei City is not simply to provide owners with shelter, more importantly, the implementation of a new ideal lifestyle.

I have a dream that one day solar industry will be as advanced as the computer industry, as mature as the home appliance industry, and as large-scale as the automobile industry. I have a dream that one day the sky will be much bluer, the water will be much clearer; our homeland will be full of sunshine and tranquil.

Energy Balance and Heat-transfer for a Water-Heating Solar Collector

The heat transfer within a solar thermal collector is complicated, and involves all the mechanisms of heat transfer that you would find in a heat transfer textbook: reflection, transmission, absorption, and emission of radiation; conduction in fins and tubes; convection of the fluid within the tubes and convective heat loss from the outside of the collector. Further, these things interact with each other in such a way that they cannot be analyzed independently. A detailed treatment of heat transfer in solar collectors may be found in Beckman and Duffie's *Solar Engineering of Thermal Processes* and equations for general calculations such as heat loss from pipes may be found in a heat-transfer text such as Incropera and DeWitt's. Just to give the reader an idea of how detailed the discussion could get, consider that some light penetrating the top surface of the glass will be reflected back up into the glass by the lower surface, and then some fraction of that will be reflected back into the glass again by the top surface, and so forth ad infinitum.

Fortunately for the practitioner, a simplified model of the theory of heat transfer within a solar collector is accurate and useful for design. The parameters of the theoretical model lend themselves to determination by testing and thus the simple method described in this book is a heuristic approach: it is based on the measured performance of rated products. The form of the equations is derived from theory, but the constants used in the equations are determined by standard testing and rating procedures. I believe that a simple heuristic model based on an energy balance and the results of a standard test procedure is sufficient for correctly sizing and estimating the performance of a solar water heating system.

Energy Balance for a Solar Collector

The First Law of Thermodynamics tells us that energy is not created or destroyed within the collector, and we can account for each type of heat gain or heat loss to calculate the useful heat delivered by the collector. The optical gain of radiant heat is given the symbol q_{solar}. The heat loss to the ambient air is

q_{loss} and the useful heat delivered is q_{useful}. The energy balance resulting from these terms is then

$$q_{\text{useful}} = q_{\text{solar}} - q_{\text{loss}} - (MC)_{\text{collector}}\, dT_c/dt \tag{4-3}$$

Where $(MC)_{\text{collector}}$ is the thermal capacitance of the solar collector mass, the energy required to raise the collector temperature by one degree (J/K or Btu/F). This is one of the values reported as a result of the standard collector performance test. The collector temperature, T_c, (C or F) would vary with position inside the collector and thus must be considered a weighted average temperature, rather than a measured temperature. For steady state operation, such as may occur in the middle of the day, the capacitance term could be neglected. Each of the terms in the energy balance is illustrated in Figure 4-6.

$$q_{\text{useful}} = q_{\text{solar}} - q_{\text{loss}} \tag{4-4}$$

Optical, Radiant, Heat Gain

Consider a glazed flat-plate transpired solar collector of area A_c (m^2) mounted in a fixed position. The solar radiation incident on the collector, I_c (W/m^2), as measured in the plane of the array, is calculated as the sum of direct-beam, diffuse, and ground-reflected radiation as described in the section of this book describing the solar resource.

The transmittance of the glass and absorptivity of the collector surface appear together as the transmittance-absorptance product because the standard rating procedure cannot disaggregate the combined effects of the cover glass and the absorber surface. The optical, radiant heat gain of the collector is then

$$q_{\text{solar}} = K\tau\alpha I_c A_c \tag{4-5}$$

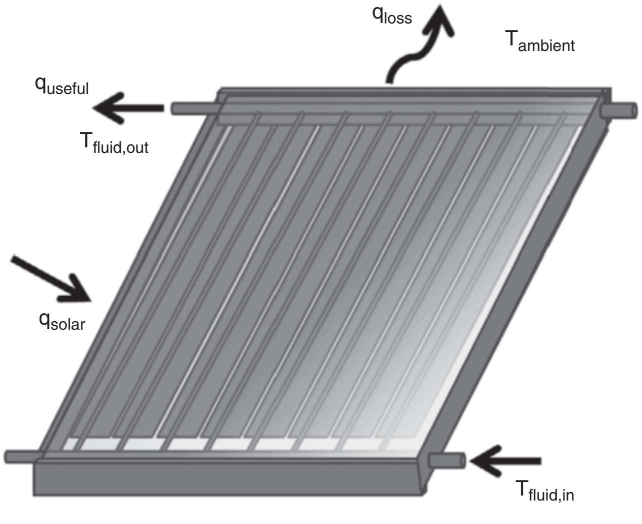

Figure 4-6. Terms in the energy balance for a solar water heating collector include solar heat gain, heat loss, and heat imparted to the fluid circulated through the collector. (Figure by the author)

Where τ is the transmissivity of the cover glass and α is the absorptivity of the absorber surface. K is the "incident angle modifier," which is defined as the ratio of $\tau\alpha$ measured at the angle of incidence of the incoming light to the value of $\tau\alpha$ measured normal to the glass. Calculation of the incident angle, $\ominus$, as a function of time-of-day and day-of-year is described in chapter 2. The form of the equation used in the standard rating procedure (ASHRAE 1977) is

$$K = 1 + b\left(\frac{1}{\cos\theta}\right) - 1 + c\left(\frac{1}{\cos\theta} - 1\right)^2 \tag{4-6}$$

Where b and c are curve-fit parameters determined by the testing procedure. Note that this equation has a problem at $\ominus = 90$ degrees, and in fact it is not accurate above 60 degree incident angle. This is of little consequence since proper collector position will result in an incident angle of less than 60 degrees when most of the solar energy is available. For greater than 60 degree incident angle, use a linear relationship between the K calculated at 60 degrees and $K = 0$ at 90 degrees. Remember that K and this equation do not include the cosine effect of the incoming solar radiation being spread over the collector area, that is taken care of in the calculation of I_c. K represents that the transmissivity of the glass is not independent of incident angle. Although it is possible to consider all three sources of radiation separately (direct beam, diffuse, ground reflection) and apply an incident angle modifier only to the direct beam component, for simplicity here we apply the incident angle modifier to I_c, the sum of all three. This simplifying assumption is consistent with the testing procedure and is justified by the fact that most heat collection is on clear days.

Thermal Heat Loss

Unglazed collectors are used in low-temperature applications, and for higher temperature applications a cover glass attenuates radiant heat loss. So the primary mode of heat loss to the ambient is convection rather than radiation and the standard rating procedure uses a linear model to describe thermal heat loss from the collector.

$$q_{\text{loss}} = U_l A_c (T_c - T_{\text{ambient}}) \tag{4-7}$$

Where U_l is the empirically-determined heat loss coefficient, the heat loss from the collector per unit area and per unit of temperature above ambient temperature (W/m^{2}C, Btu/hrFft^2).

Here again, the collector temperature T_c is not a single measured temperature but rather an average; we will see below how the standard rating procedure correlates the heat loss to incoming water temperature via the relationship of heat exchanger effectiveness. Some practitioners, especially in Europe, prefer a second-order heat loss model, especially if higher-temperature performance of evacuated tubes is being considered. Radiant heat loss is important for unglazed collectors as well. The SRCC OG-100 Rating reports both linear and second-order heat loss coefficients. Equation for second-order heat loss is of the form:

$$q_{\text{loss}} = U_{l\,1}\, A_c(T_c - T_{\text{ambient}}) + U_{l2}A_c(T_c - T_{\text{ambient}})^2] \qquad (4\text{-}8)$$

Since we are going to use the empirically-measured heat loss coefficient, U_l, we don't need to calculate all the mechanisms of heat loss from the solar collector; but it is useful to consider some of them in detail so that we can discuss the source of differences between collectors, and also so that we can correct for a fluid flow rate different than that of the empirical measurement. The radiant heat loss from the absorber plate to the ambient is given by Duffie and Beckman (2006)

$$q_{\text{loss, radiant, plate to sky}} = \frac{\tau\varepsilon\sigma(T_{\text{plate}^4} - T_{\text{sky}^4})}{(1 - \rho_{\text{plate}}\ \rho_{\text{cover}})} \qquad (4\text{-}9)$$

Where τ and ρ_{cover} are the transmissivity and underside reflectivity of the cover glass and ρ_{plate} is the reflectivity of the absorber plate. A very thin layer of metal oxide (tin oxide) on the underside of the glass will reflect more radiation back down onto the absorber plate, but since it would also reduce the solar transmittance, is recommended only for collectors designed to operate at a high temperature. For an unglazed collector τ is equal to 1 and ρ_{cover} is zero.

Radiant heat loss is proportional to ε, the emissivity of the absorber plate, the temperature to the forth power, and the constant of proportionality is σ, the Stephan-Boltmann constant equal to 5.6697×10^{-8} W/m^{2}K^4. (Note; when multiplying or dividing temperature, the units must be in units of absolute temperature: Kelvin or Rankine (K or R), not celsius or fahrenheit). Radiative heat loss is important for unglazed collectors and for collectors operating at elevated temperatures. In all cases, an absorber plate with a low emissivity would reduce heat loss from the solar collector. On the back side of the absorber plate we can leave it shiny metal and have a low emissivity, but on the front side we seek an absorber surface with a high absorptivity to trap more solar radiation. For most common materials, the absorptivity equals the emissivity, but since the 1950s, surfaces have been fabricated that have a low emissivity in the long wavelength being emitted from the surface and a high absorptivity in the short-wavelength solar spectrum. Such surfaces with a low emissivity and a high absorptivity are called "selective surfaces." Surfaces with absorptivity above 0.95 in the solar spectrum and emissivity, ε, as low as 0.10 in the thermal heat loss spectrum are available.

CONCEPT

"Selective Surfaces"

The second law of thermodynamics requires that absorptivity of radiation equals emissivity of radiation, but only at a given wavelength. By manipulating the mechanisms of absorption that occur at different wavelengths, it is possible to construct a surface that has a high absorptivity in the solar spectrum but a low emissivity in the longer-wavelength infrared spectrum, and thus better trap the radiant heat. The first selective surfaces consisted of a base of shiny metal, such as copper, which naturally has a low emissivity, and then applying a thin layer of black metal oxide. The thin metal oxide layer is too thin to act as an "antenna" for the generation of long-wavelength thermal heat loss radiation, but has a high absorptivity in the short-wavelength solar spectrum by the mechanism of "destructive optical interference". This mechanism indicates that multiple thin layers of different thicknesses would be most effective. An early successful selective surface was created by electroplating nickel onto the copper absorber and then electrodeposition of chromium oxide. A layer of semiconductor material with a band gap matching that of the solar spectrum has a high absorptivity, but when layered on a metal substrate with a low emissivity at longer wavelengths creates a selective surface. Multilayer absorbers use multiple reflections between layers to absorb light. Ceramic-metal composites, called cermets, suspend microscopic metal particles in a ceramic substrate. Surfaces can be textured to produce high solar absorptance by trapping reflected light (Kennedy 2002).

A selective surface can improve the performance of a solar collector by about 20 percent, depending on the operating temperature. Table 4-3 lists the much different values for solar absorptivity and thermal emissivity typical of several types of selective surfaces.

TABLE 4-3. SOLAR ABSORPTIVITY AND THERMAL EMISSIVITY OF "SELECTIVE SURFACE" MATERIALS

Surface	Absorptivity in solar spectrum	Emissivity in spectrum of infrared heat loss
Black chrome	0.920	0.085
Black anodized aluminum	0.93	0.070
Tin oxide (TnOx)	0.92	0.06
Ceramic metal (cermet)	0.96	0.08
Textured stainless steel	0.93	0.22

Another detail of collector heat loss that we can consider is the integrity of the thermal insulation. The heat loss by conduction through the plane of insulation on the back of the module is

$$q_{\text{loss, conduction}} = \frac{k_{\text{insulation}}}{t_{\text{insulation}}} A_c(T_c - T_{\text{ambient}}) \qquad (4\text{-}10)$$

Where $k_{\text{insulation}}$ is the thermal conductivity and $t_{\text{insulation}}$ is the thickness of the slab of insulation. Thickness of the insulation necessarily adds to the thickness of the collector. For swimming pools in hot climates, it may be counterproductive to insulate the absorber plate because a T_{ambient} greater than T_c would force heat from the ambient air into the swimming pool water, which is desirable. But for most applications we seek insulating material with a very low value for k, or in other terms a very high "R-value." Materials used to insulate solar collectors must tolerate a high temperature and include fiberglass and polyisocyanurate. Most of these materials have a value for k around 0.030 W/mC. Silica Aerogel is an advanced material with a conductivity of only 0.004 W/mC, but such materials have yet to find their way into solar collector manufacturing. The material with the lowest value of k is no material at all: a vacuum. Within a vacuum there is no air or other media to conduct heat away from the absorber plate. If we were to evacuate the air out of a flat-plate collector, the atmospheric pressure would buckle and break the cover glass. But if the cover glass is in the shape of a tube, then all the elements of glass are in compression (glass is very strong in compression) with the atmospheric pressure pushing equally around the tube. Into this evacuated tube may be inserted absorber plates of various geometries with different strategies of how to circulate the fluid to be heated through the enclosure of the vacuum (rubber or glass seals). The vacuum so created must be maintained for a very long period of time, and "getters" of barium or other material are installed in the tubes to absorb gasses that have diffused into the tube and indicate if a tube barrier has failed. Collectors employing this approach are called "evacuated-tube" solar collectors.

Useful Heat Delivery of the Solar Collector

The useful heat delivered by the collector is the difference between the optical, radiant energy gain and the thermal heat loss from the collector.

$$q_{\text{useful}} = \tau\alpha A_c K I_c - U_l A_c (T_c - T_{\text{ambient}}) \qquad (4\text{-}11)$$

The useful heat delivered by the solar collector is manifest in an elevation of temperature of the outlet over that of the inlet and may be calculated as

$$q_{\text{useful}} = mc_p(T_{\text{fluid,out}} - T_{\text{fluid,in}}) \qquad (4\text{-}12)$$

where

m = mass flow rate of water through the solar collector, kg/s

c_p = specific heat of the water being heated, around 4.20 kJ/kgK for pure water, lower for other heat transfer fluids.

$T_{\text{fluid, in}}$ = the temperature of the cold fluid coming into the solar collector (C)

$T_{\text{fluid,out}}$ = the temperature of the heated fluid exiting the solar collector (C)

We have two unknowns, the collector temperature T_c and the fluid outlet temperature $T_{\text{fluid,out}}$, but we have only one equation (conservation of energy). In order to solve for the two unknowns we need to introduce another equation: the effectiveness relation of the heat exchanger which expresses $T_{\text{fluid,out}}$ as a function of T_c. The solar collector is a heat exchanger. There are two ways of calculating net heat transfer across a heat exchanger: 1) the log-mean temperature difference (LMTD) method and; 2) the number of transfer units (NTU)-effectiveness method. The LMTD method is useful when both the inlet and outlet temperatures are known. However, in this case we know only the incoming cold water temperature, so the NTU-effectiveness method is used (Incropera and DeWitt 2005). Heat exchanger effectiveness, e_{hx}, is generally defined as the ratio of actual heat transfer to ideal heat transfer, but in this case it is defined as the ratio of actual heat transfer (based on the actual outlet and inlet temperatures) to heat transfer if the mass flow rate of water is heated from inlet temperature $T_{\text{fluid, in}}$ to the already-defined reference collector temperature, T_c.

$$q_{\text{useful}} = mc_p(T_{\text{fluid,out}} - T_{\text{fluid,in}}) = mc_p e_{hx}(T_c - T_{\text{fluid,in}}) \qquad (4\text{-}13)$$

Effectiveness is expressed as a function of a dimensionless parameter called NTU for "number of transfer units". For most heat exchangers, the effectiveness also depends on the capacitance flow rate, mc_p, of the fluid *from* which the heat is transferred, and the cooling of this stream limits the heat transfer. But our solar collector has only one fluid, the fluid *to* which the solar heat is transferred, and the effectiveness equation reduces to the very simple relation

$$e_{hx} = 1 - e^{-\text{NTU}} \qquad (4\text{-}14)$$

Collector performance may be correlated with other temperatures associated with the collector, and various temperatures have been used in early studies including the outlet temperature and average of inlet and outlet temperatures (Winn et al. 1980). It really doesn't matter what temperature is used, as long as the heat exchanger effectiveness is defined and calculated accordingly and the temperature used correlates well with collector heat delivery. In fact, we will conclude this section with definition of the heat removal factor, F_R, which is the effectiveness based on the fluid inlet temperature.

NTU, number of transfer units, is the dimensionless ratio of heat transfer to capacitance. The definition of NTU is the heat transfer coefficient (W/C, or Btu/h/F) divided by the mass flow rate times the specific heat of the water (W/C or Btu/h/F). Without naming it as such, Duffie and Beckman (2006) identified the NTU based on the parameters of the solar collector model as

$$NTU = \frac{AcU_lF'}{mcp} \qquad (4\text{-}15)$$

Where: F′ is the "collector efficiency factor," the actual gain divided by the gain if the entire absorber plate were at the local fluid temperature. F′ depends on the absorber plate geometry and material properties. For the tube-in-plate geometry shown in Figure 4-7, F′, is provided by Duffie and Beckman (2006).

$$F' = \frac{1}{\dfrac{WU_l}{Dh_{\text{int}}} + \dfrac{W}{D+(W-D)F}} \tag{4-16}$$

U_l = loss coefficient to the ambient, as before, and h_{int} is the convective coefficient on the inside of the collector riser tubes. F is the fin efficiency factor, which considers the absorber plate as a fin conducting heat to the riser tube and is given by Incropera and Dewitt as

$$F = \frac{\tanh\left[\dfrac{(W-D)\sqrt{\dfrac{U_1}{t_{\text{plate}}k_{\text{plate}}}}}{2}\right]}{\left[\dfrac{(W-D)\sqrt{\dfrac{U_1}{t_{\text{plate}}k_{\text{plate}}}}}{2}\right]} \tag{4-17}$$

where k is the conductivity of the absorber plate material and t_{plate} is the absorber plate thickness. Figure 4-7 defines the geometric parameters typical of a fin-and-tube absorber plate arrangement.

Since T_c is an average, not a measured quantity, we seek an equation to calculate the useful heat gain of the collector based on incoming fluid temperature instead of any internal collector temperature. This makes it possible to calculate the outlet temperature, heat gain, and efficiency as functions of environmental conditions: intensity of sunlight, ambient temperature, and incoming water temperature. The ratio of actual heat gain to heat gain calculated with $T_{\text{fluid,in}}$ in place of T_c is called the "heat removal factor" and given the symbol F_R. Duffie and Beckman provide the equation for F_R

$$F_R = \frac{mc_p}{A_cU_l}[e_{hx}] \tag{4-18}$$

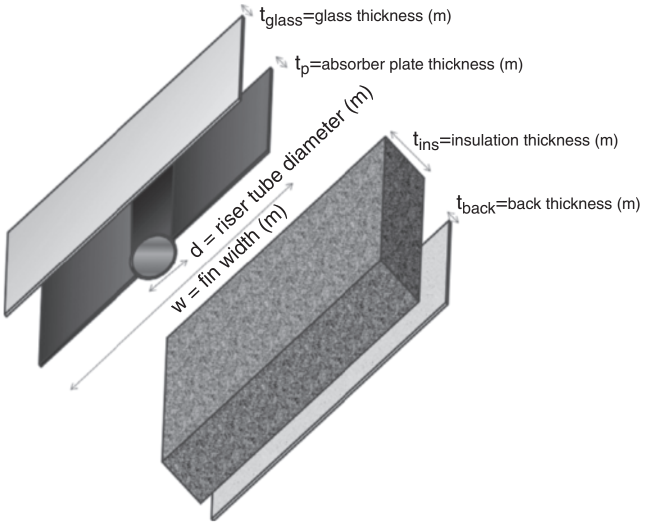

Figure 4-7. This figure defines the geometry used to calculate heat-transfer effectiveness within a fin-and-tube type solar collector. (Figure by the author)

TIP

Mass Flow Rate, m (kg/s, lbm/hr), other than Rated Flow Rate

Parameters of solar collector performance depend on the heat removal factor F_R which in turn depends on the mass flow rate through the collector. The values of $F_R\tau\alpha$ and F_RU_l reported for the standard rating procedure will be based on the mass flow rate used in the rating test. For many projects, use of the rating flow rate is appropriate. But sometimes whole-system considerations, such as trying to enhance stratification in a storage tank, or minimizing pipe diameter, result in a specified flow rate much lower than the rating flow rate. Another such consideration is trying to make a lesser volume of water hotter more quickly and be ready for a hot water load draw earlier (albeit at the expense of collector efficiency). For flow rates other than the rated flow rate, the measured collector parameters $F_R\tau\alpha$ and F_RU_l should be divided by the F_R calculated at the rating flow rate and multiplied by the F_R calculated at the specified flow rate. Above we follow Duffie and Beckman's (2006), derivation of F_R for a certain fin-tube geometry, but other collectors may have different geometries. Manufacturers may ask that their collectors be tested at different flow rates and add these rating to the SRCC rating report (SRCC 2012), but since this adds to the cost of the rating, most manufactures just report the efficiency at one flow-rate. Until and unless testing provides F_R as a function of flow rate, I would recommend using the equation above for a fin-tube geometry, or consult the manufacturer of the solar collector regarding use at flow rates other than the testing and rating flow rate.

Finally we arrive at a very useful equation that is of the form where all the parameters may be measured by the standard test procedure. This is known as the Hottel-Whillier-Bliss equation in honor of the people that contributed to its development in the 1940s.

$$q_{\text{useful}} = F_R\tau\alpha A_cKI_c - F_RU_lA_c(T_{\text{fluid,in}} - T_{\text{ambient}}) \tag{4-19}$$

Equation 4-19 provides a way of calculating the useful heat delivery of the solar collector as a function of the measured properties of the solar collector $F_RK\tau\alpha$ and F_RU_l; the extant environmental conditions I_c and T_{ambient}, and the temperature at which the collector is supplied with water to be heated, $T_{\text{fluid,in}}$. (Smith and Weiss 1977).

Concept

Hottel-Whillier-Bliss Equation

This very useful equation is known as the Hottel-Whillier-Bliss equation in honor of Hoyt Hottel at Massachusetts Institute of Technology and the researchers who developed it in 1942.

$$q_{\text{useful}} = F_R \tau\alpha A_c K I_c - F_R U_l A_c (T_{\text{fluid,in}} - T_{\text{ambient}}) \qquad (4\text{-}20)$$

The equation gives the heat delivery from a solar collector as a function of environmental conditions: sunlight, ambient temperature, and incoming fluid temperature.

If all the other parameters are known, we may rearrange the energy balance equation and solve for T_c. Up to now we've described this parameter as an average that is not measured directly. The temperature in the collector will be a minimum near the cold fluid inlet and a maximum at a location on the absorber surface farthest from a riser tube. The temperature drops as the heat is conducted down the absorber plate to the riser tube, and then increases along the length of a riser tube. But we can calculate a value for T_c and also render some interpretation: The solar energy coming into the collector is split between losses (based on the loss coefficient) and useful heat gain (based on the heat exchanger effectiveness). Both of these heat flows depend on T_c, but one losing heat to T_{ambient} and the other to $T_{\text{fluid,in}}$. We interpret T_c as an abstract concept of the temperature around which both of these linear models make the energy equation balance.

We are able to solve for T_c directly because of the simple linear formulation of the terms in the energy balance.

$$T_C = \frac{I_C \tau\alpha A_C + U_l A_c T_{\text{ambient}} + e_{hx} \text{mc}_p T_{\text{fluid,in}}}{(U_l + e_{hx} \text{mc}_p)} \qquad (4\text{-}21)$$

If we want to consider a second-order heat loss term, or radiant heat loss, we can add these more detailed terms to the energy balance, but we could then not solve this equation directly for T_c because it is squared in the second-order heat loss term and raised to the fourth power in the term accounting for radiant heat loss. Also, if we consider the time rate of change of temperature over time (nonsteady-state, transient case), then we wouldn't be able to solve for T_C directly because it appears in $dT_{C/dt}$. In these cases, the equation is solved by iteration: guess a value for T_C and then adjust that value until the right hand side of the energy balance equation equals the left hand side. Microsoft Excel has a feature that makes it really easy to solve equations by iteration, as do many other mathematical software tools.

Another interesting result of the energy balance analysis is the *stagnation temperature*, the temperature that the collector would approach if there were no fluid flow through the collector.

$$T_{\text{stagnation}} = I_C \tau\alpha / U_l + T_{\text{ambient}} \qquad (4\text{-}22)$$

If this is calculated using "worst case" conditions of highest solar insolation (perhaps 1,200 W/m^2) and highest ambient temperature (perhaps 40C), it gives an indication of the high temperature that the materials the solar collector is constructed of may have to withstand, perhaps exceeding 200 C (400F). High temperature causes off-gassing from binders and other chemicals in the insulation, degrades absorber surface coatings, and ruins seals around the box enclosure of the collector. Quality collectors must be able to tolerate this stagnation condition as it is inevitable that flow through the collector will be interrupted at some time, such as when a pump is removed for maintenance.

Having determined the value of q_{useful} or T_C, we may calculate the temperature of the fluid exiting the solar collector

$$T_{\text{fluid,out}} = T_{\text{fluid,in}} + \frac{q_{\text{useful}}}{\text{mc}} = T_{\text{fluid,in}} + e_{hx}(T_c - T_{\text{fluid,in}}) \qquad (4\text{-}23)$$

Thermal Capacity

The thermal capacity of the collector is a parameter reported in the standard collector test and represents energy stored in the temperature of the collector itself. This capacitance, along with the capacitance of the pipe and fluid in the collector loop, has a significant effect on the system performance. Each morning, solar heat is used to heat the collector up to a temperature at which it can heat the water. Then at night, when the collector cools to a temperature less than the water, this warm-up heat is not recovered and is wasted. Therefore, collectors with a low thermal capacity are preferred. The thermal capacity of the collector, $(\text{MC})_{\text{collector}}$, is expressed in kWh per m^2 collector area and per degree C of temperature increase. The lower the thermal capacity of the collector, the better. The power associated with energy stored or released from the solar collector is $(\text{MC})_{\text{collector}\ dTc/dt}$.

Efficiency Curves for Solar Water Heating Collectors

The efficiency, η, of the solar collector is defined as the useful heat delivered by the solar collector divided by the incident solar power:

$$q_{\text{useful}} = F_R \tau\alpha A_c K I_c - F_R U_l A_c (T_{\text{fluid.in}} - T_{\text{ambient}}) \qquad (4\text{-}24)$$

$$\eta = \frac{q_{\text{useful}}}{I_c A_c} = \frac{F_R \tau\alpha A_c K I_c - F_R U_l A_c (T_{\text{fluid,in}} - T_{\text{ambient}})}{I_c A_c}$$

$$= F_R \tau\alpha K - \frac{F_R U_l (T_{\text{fluid,in}} - T_{\text{ambient}})}{I_c} \qquad (4\text{-}25)$$

All of the parameters in this expression for efficiency are known, either as environmental conditions or as properties of the collector measured in the standard performance test. Thus we may solve for efficiency using this equation without iteration. The first term of Equation 4-25 is the optical gains coefficient and depends only on the optical properties of the collector. Solar collector efficiency is very dependent upon incident solar, I_C, and the difference between fluid temperature and ambient temperature. These parameters form a parameter called the "inlet parameter" $(T_{\text{fluid,in}} - T_{\text{ambient}})/I_C$. Thus, if we consider only first-order losses the curve of efficiency as a function of the inlet parameter is a straight line with a y-intercept equal to the optical gains coefficient $F_R\tau\alpha K$ and a slope equal to the loss coefficient F_RU_L.

The collector area, A_C, that appears in the Equation 4-24 for useful heat delivery of a solar collector is usually defined as the "gross" area: the total area occupied by the solar collector including frame. Other definitions have been used, such as glass area or absorber plate area. Performance may be correlated with any of these, as long as the area definition used in the useful heat calculation is the same area used in subsequent design calculations. In this book we refer to A_C as the gross area only, and this is consistent with the definition in the standard rating procedure.

Figure 4-8 shows the reported efficiency of the three types of solar collectors as a function of the inlet parameter. The theory presented above results in a linear efficiency equation, but the standard test procedure also reports the coefficients of a quadratic curve fit of efficiency.

We may draw some important conclusions by referring to the solar collector efficiency curves:

At low values of the inlet parameter (low incoming water temperature), the unglazed collector has the highest efficiency. The unglazed collector has the highest optical gains coefficient (y-intercept) because it has no cover glass to reflect or absorb radiation. However, as temperature increases, the efficiency of the unglazed collector drops off due to excessive heat loss (steep slope of efficiency line).

At values of the inlet parameter typical of domestic water heating, glazed flat-plate and evacuated-tube collectors have about the same efficiency.

At low values of the inlet parameter (low temperatures), evacuated-tube collectors have a lower efficiency than the other types, but at higher temperatures, the superior insulation of an evacuated tube (gradual slope of efficiency line) maintains a useful efficiency. The evacuated tube has a low optical gains coefficient due to reflection off the curved tubes, but a very low loss coefficient, even at elevated temperatures.

Example Calculation of Solar Water Heating Collector Performance based on Rating Data

In this example we calculate the instantaneous performance of a glazed flat-plate solar collector under specified ambient conditions using the results of the performance test, and then modified to account for a flow rate other than the specified flow rate.

We refer to the SRCC OG-300 Solar Collector Rating and Certification sheet for the collector under consideration. The report lists out the coefficients for both a linear and quadratic curve fit of efficiency versus the inlet parameter. The incident angle modifier is reported by the test data as $K = 1–0.078^*(1/\cos(\ominus)–1)–0.086^*(1/\cos(\ominus)–1)^2$ The collector has an area

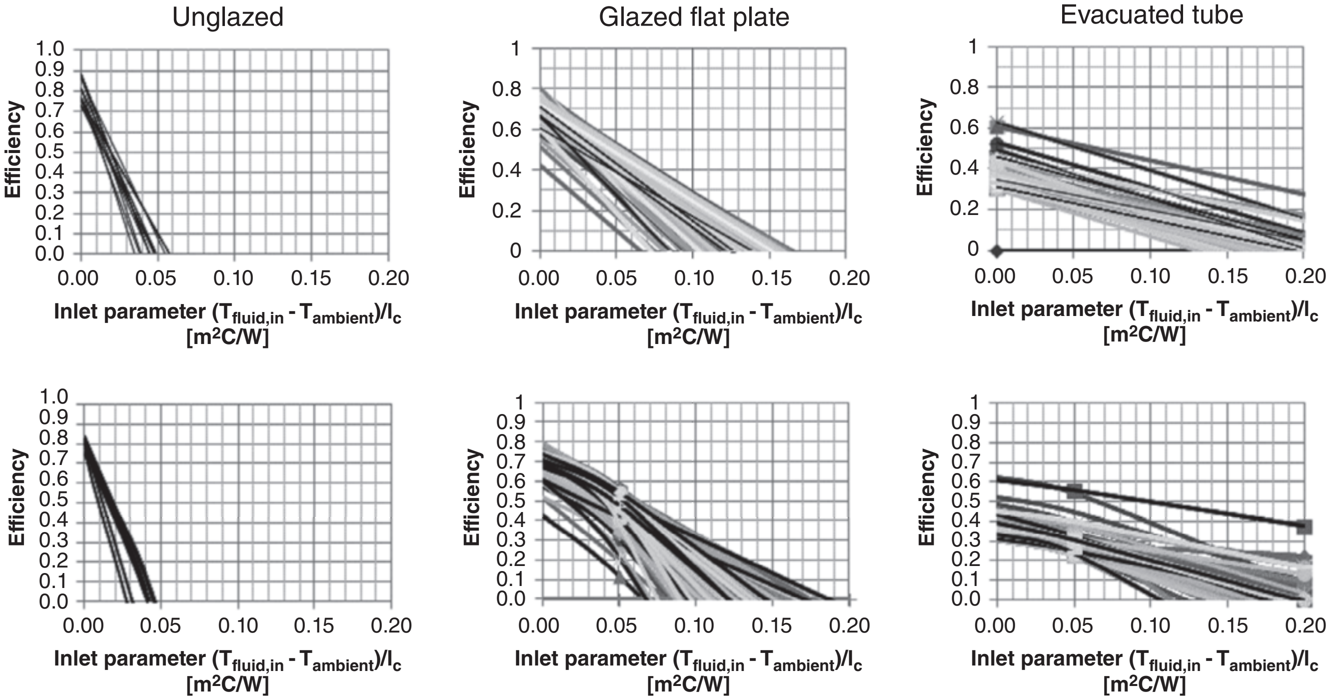

Figure 4-8. Range of efficiency of unglazed, glazed flat-plate, and evacuated-tube solar collectors as a function of the inlet parameter $(T_{\text{fluid,in}} - T_{\text{ambient}})/I_C$. Each line is for a different collector make and model. Upper three charts are linear curve fits; lower three curves are quadratic curve fits. (Figure by the author using data from SRCC available at solar-rating.org)

TABLE 4-4. EXAMPLE CALCULATION OF SOLAR WATER HEATING COLLECTOR ENERGY COLLECTION AND EFFICIENCY AS A FUNCTION OF ENVIRONMENTAL CONDITIONS

Fluid flow rate			
V	fluid volume flowrate	0.08 l/s	(1.282 gpm)
m	fluid mass flowrate	0.09 kg/s	(681 lbs/hr)
Ambient conditions			
I_C	solar radiation	500 W/m^2	(158.6 Btu/hft^2)
$T_{ambient}$	ambient temperature	0 C	(32.2 F)
$T_{fluid,in}$	entering fluid temperature	30 C	(81.0 F)
Solar liquid-heating collector dimensions and properties (test results)			
W	Width	1.2 m^2	(4.0 Ft)
L	Length	3.1 m^2	(10.1 Ft)
Ac	Area	3.7 m^2	(40.2 ft^2)
$Fr_{\tau\alpha}$	optical gains coefficient	0.752	
F_RU_L	heat loss coefficient	4.02 W/m^2/C	(0.710 Btu/hr/ft^2/F)
K	Incident angle modifier Equation 4-6	0.836	
Energy balance			
q_{solar}	Optical solar gains Equation 4-5	1173 W	4002 Btu/hr)
q_{loss}	Heat loss Equation 4-7	450 W	1535 Btu/hr)
q_{useful}	Heat delivery Equation 4-19	722.9 W	2466.6 Btu/hr)
Results			
$T_{fluid,out}$	Fluid out temperture Equation 5-23	32.3 C	(90.4 F)
$\eta_{Collector}$	Collector efficiency Equation 5-25	0.387	

of 3.732 m^2 (40.15 ft^2). The rating reports the optical gains coefficient $F_R\tau\sigma$ and the heat loss coefficient F_RU_l. The volume flowrate is 22.2 ml/s/m^2 of collector area (0.0328 gpm/ft^2). The ambient conditions are: 500 W/m^2 (158 Btu/ft^2/hr) solar incident on the wall; and 0°C (32.2°F) ambient temperature. We are asked to calculate the rate at which heat is delivered by the collector; the temperature of the heated fluid exiting the solar collector; and the efficiency. The heat-transfer fluid is a solution of 50 percent propylene glycol and 50 percent water by weight. We use the thermophysical properties of this solution at 30°C (81°F), although looking up the properties again once we know the average fluid temperature would improve accuracy. We proceed through the equations of this chapter, and the results from each equation are listed in Table 4-4 in the order that they are calculated.

We find that under these conditions, the solar collector would deliver heat at the rate of 723 W (2,467 kBtu/hr) and heat the stream of fluid from 30°C (81°F) to 32.3°C (91) temperature. Thus, even under the cold and slightly cloudy conditions considered here, the solar collector operates at a reasonable efficiency and delivers a significant amount of heat. The efficiency is calculated at 38 percent in this example.

SOLAR WATER HEATING SYSTEM SCHEMATIC DESIGN

Schematic design of a solar water heating system specifies the size, type, and location of major components. There are several different system concepts that compete in different

TABLE 4-5. COMPARISON OF DIFFERENT TYPES OF SCHEMATIC DESIGNS FOR SOLAR WATER HEATING SYSTEMS

	Simple, low cost	Low power consumption	Avoid scaling and corrosion	Low maintenance	Freeze protection	Overheat protection
Integrated collector storage (ICS)	*	*	*	*		
Thermosyphon	*	*		*		
Direct	*					
Indirect coil-in-tank			*		*	
Indirect heat exchanger			*		*	
Indirect drain-back			*		*	*

applications. The schematic phase of design should list out the following details regarding components:

> Solar collector: type of solar collector (unglazed, glazed, evacuated-tube, concentrating); collector area, m^2 (ft^2); fluid flow rate, l/s (gallons per minute); pressure drop, kPa (psi); optical gains coefficient; heat loss coefficient, $W/m^2/C$ ($btu/hr/F/ft^2$); frame material and finish, location, and type of attachments to structure.
>
> Pump: total pressure drop, Pa (psi or inches of water column) around collector loop or potable water loop; fluid flow rate of heat-transfer fluid at design conditions, l/s (gpm); and flow rate of water in the potable water loop.
>
> Overheat protection: strategy to avoid overheating of collector fluid (drain back, temperature actuated solenoid valve)
>
> Pressure relief protection: any tank or heat-producing component that may be valved off requires pressure relief valve.
>
> Controller: the schematic design describes central or local controls and control sequence.
>
> Bypass piping: valves that allow the solar heating system to be valved off during maintenance, with hot water being provided using only the conventional heater.
>
> Tempering valve: mixes water that is too hot with cold water before delivery to users.

Solar water heating systems are classified as “direct” if they heat potable water directly and “indirect” if they heat an intermediary heat-transfer fluid first. Systems are classified as “active” if they require electric power to operate pumps and controls and as “passive” if they use natural buoyancy to circulate fluid without pumps. Each of these has advantages and disadvantages depending on the needs of the application such as freeze protection and the availability of electric power for pumps and controls as indicated in Table 4-5. Each of several types is discussed according to: cost; power consumption; resistance to water quality problems such as scaling and corrosion; maintenance requirements; freeze protection; and protection against system overheating.

Direct Passive Integrated Collector Storage (ICS) System Schematic

The simplest schematic diagram for solar water heaters is to simply expose a tank of water to the direct solar heat. This is the oldest type of solar water heater and still quite common in nonfreezing climates. Valves are positioned such that cold water flows into the storage volume within the solar collector, and just by the pressure in the water lines hot water flows out of the collector and into a conventional water heater.

The storage volume is created within the insulated collector enclosure by large diameter pipes that form tanks. Water is distributed between the tanks in the collector by connecting pipes. A cut-away view photograph of such an integrated storage collector is provided in Figure 4-9.

The cost of an ICS system is low compared to other system types due to the small number of system components required. The passive ICS system requires no power to operate, making it desirable for use in places where power is expensive or unavailable. While the surfaces are exposed to a circulation of potable water, the impacts of scaling are mitigated by the large flow

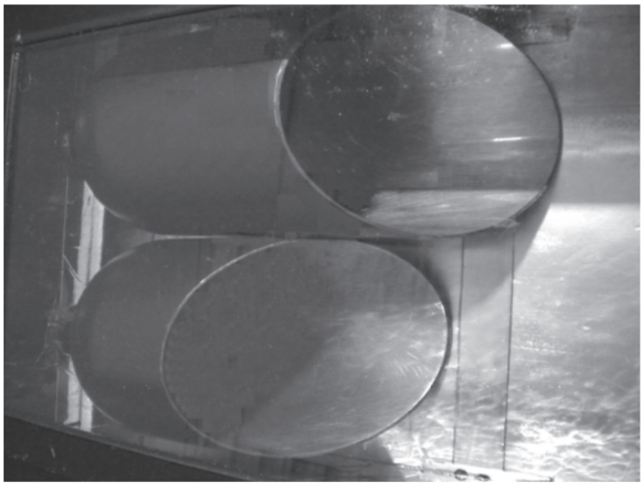

Figure 4-9. Cut-away view of integrated collector storage (ICS) type of solar collector shows large-diameter copper tubes which store the solar-heated water inside the collector. (Photo by the author)

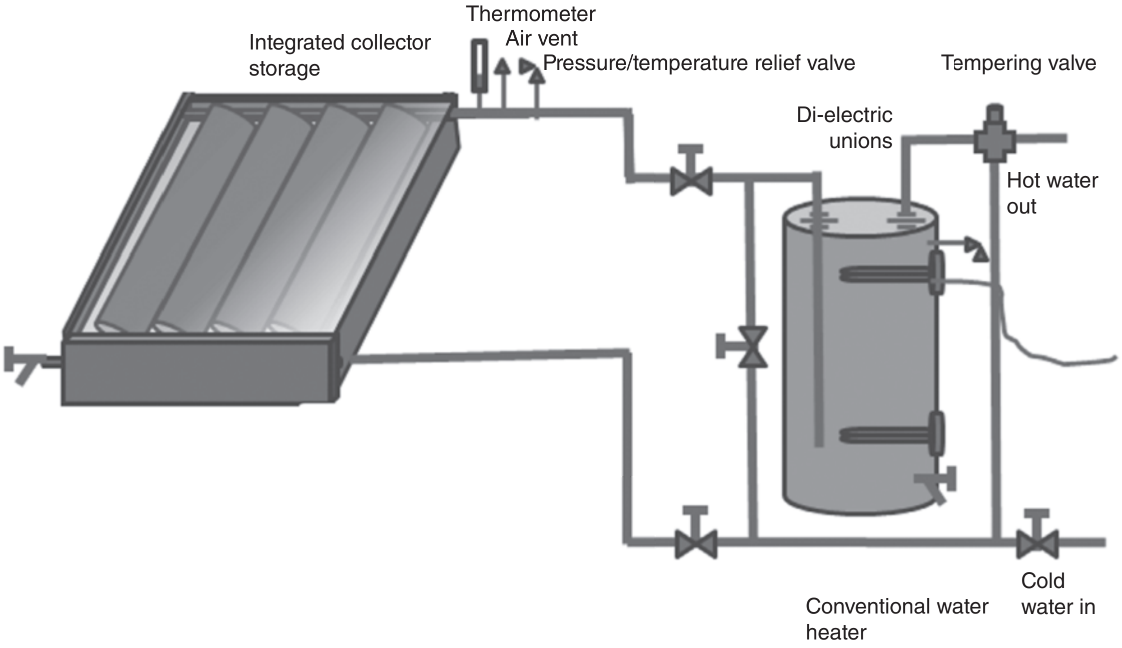

Figure 4-10. Schematic diagram of integrated storage collector (ICS) system. (Figure by the author)

passages. With no pumps or active controls, the maintenance requirements of an ICS system are very low. One manufacturer warrants the collector against freezing, but pipes of potable water to and from the system are susceptible to freezing and rupture. There is no built-in protection against overheating of the water in the collector if there is no hot water use. The only thing separating our hot water storage from the cold night sky is a single sheet of glass, so heat loss of the ICS type of collector can be excessive. Due to lack of freeze protection and excessive heat loss, the ICS type of system is most suitable for warm climates. Some roof situations may not be able to accommodate the weight of the water storage on the roof. Figure 4-10 is a schematic diagram of an ICS system showing also balance of system components.

Direct Passive Thermosyphon System Schematic

In order to reduce heat loss, the thermosyphon system puts the storage in a well-insulated storage tank above the collector, as shown in Figure 4-11, and uses the buoyancy of hot water inside the collector to cause a circulation of hot water from the collector outlet up into the storage tank and cold water back down from the storage tank to the collector inlet. These systems are available with the conventional electric heating element in the single water storage tank, or may preheat for a separate conventional water heater.

The cost of a thermosyphon system is low compared to other system types due to simplicity. The passive thermosyphon

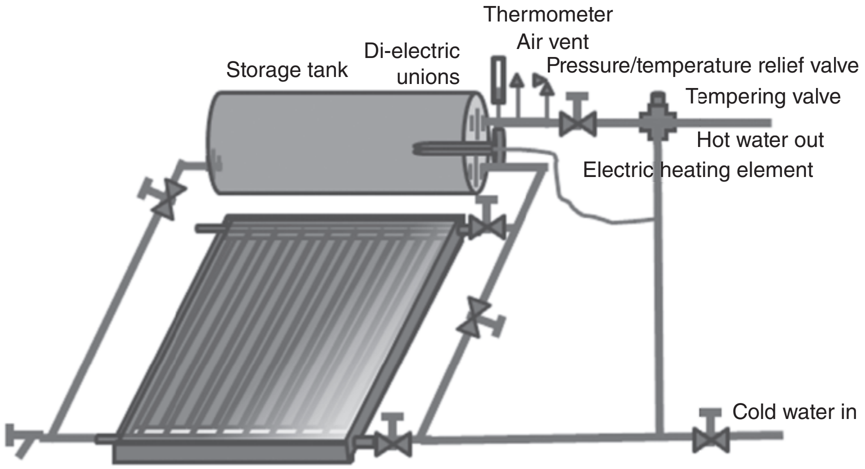

Figure 4-11. Schematic diagram of thermosyphon solar water heating system, which relies on the tank being located above the collector for natural circulation. (Figure by the author)

system requires no electric power to operate. Due to circulation of potable water through the small flow passages in the collector, the system is susceptible to scaling and corrosion. The maintenance requirements are very low. If the system circulates potable water, it is vulnerable to damage by freezing. There is no built-in protection against overheating of the water in the collector if there is no hot water use for an extended period of time. Natural convection causes the collector surface to operate at a higher temperature than pump-forced convection, so thermal efficiency is lower than active systems. Due to lack of freeze protection and elevated temperature, the thermosyphon system is used only in warm climates.

Some roof structures may not accommodate the heavy storage tank without modification.

Direct Active Solar Water Heating System Schematic

It is often desirable to put the large heavy storage tank in the basement or on the ground, and thus one single pump is required to overcome buoyancy and circulate water between the tank and the solar collector on the roof. This entails the cost of the pump but also two temperature sensors and a controller to turn the pump on and off. Electric power is provided to the pump and the controller. Figure 4-12 shows a schematic diagram of a direct active solar water heating system.

Cool water to be heated is drawn from the cold water line or the bottom of the storage tank, and a conventional heating element often heats the top of the tank. Using only one tank increases the average operating temperature of the collector, and decreases the efficiency, due to mixing within the storage tank. The solar collector riser tubes are exposed to potable water which increases scaling and corrosion. Exposure of other system components, such as the pump, to potable water also increases maintenance. The system is not protected against freezing and there are no provisions to preclude overheating.

Another application of direct active configuration is for heating swimming pool water, as shown in Figure 4-13. A pool filter system consists of a strainer, pump, pool filter, and natural gas-fired or electric heater. Since these components would exist anyway we do not include them in the schematic diagram of the solar heating system. The components shown in the following figure are placed between the filter and the heater, so that the solar preheats for the conventional heater (or the conventional heater is turned off). Due to the low-temperature operation, unglazed plastic collectors and plastic pipe are generally used in swimming pool heating systems. A diverter valve controlled by a "delta T" controller may be used to route water to the solar collector for heating or directly to the conventional pool heater. If freezing conditions are imminent, the solar collector is valved off from the pool filter and heater system using provided valves and drained completely of water.

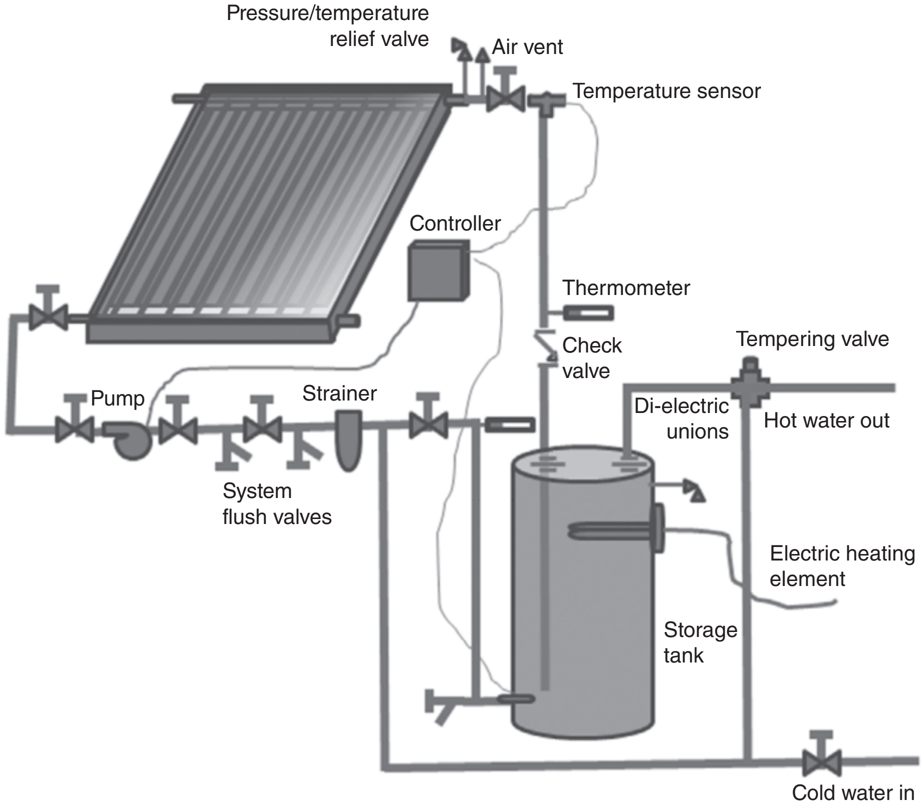

Figure 4-12. Schematic diagram of direct solar water heating system, which circulates potable water through the solar collector. (Figure by the author)

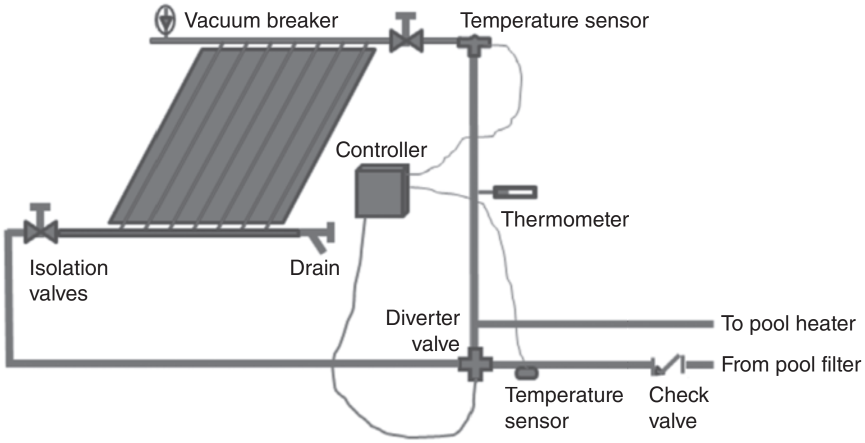

Figure 4-13. Schematic diagram of direct active solar heating in which swimming pool water is circulated through the solar collectors. (Figure by the author)

Indirect Active Solar Water Heating System Schematic with Heat Exchanger

The "indirect" system schematics circulate a nonfreezing heat-transfer fluid through the solar collector and then transfer the solar heat to the potable water by means of a heat exchanger. A second pump is required to circulate the potable water from the storage tank through the other side of the heat exchanger. Both pumps are controlled by the same controller.

The schematic diagram of Figure 4-14 shows the components of an indirect active solar water heating system. An indirect system is more expensive because it has two pumps, the heat exchanger is expensive, and also the heat-transfer fluid itself is rather expensive. Electric power must be provided to both pumps

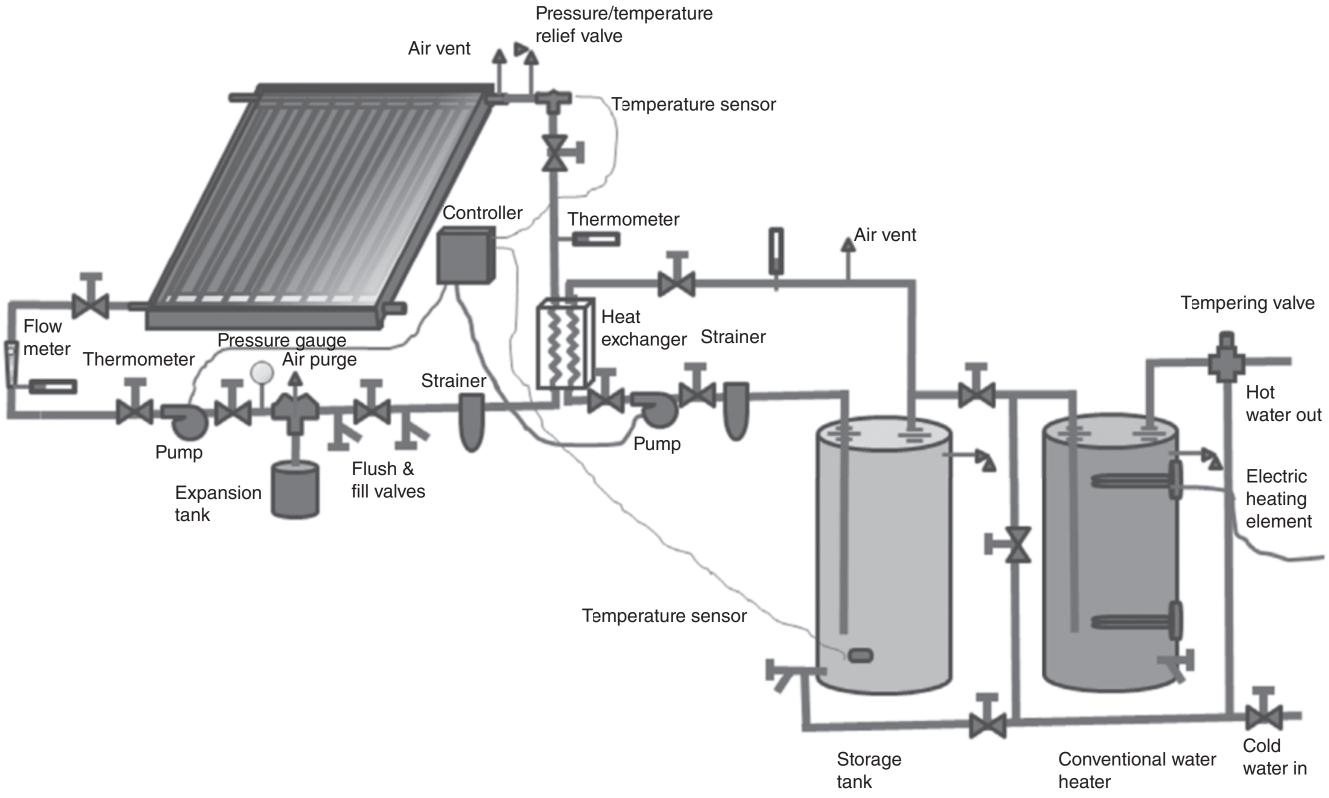

Figure 4-14. Schematic diagram of indirect solar heating with heat exchanger to transfer heat from a heat-transfer fluid, which circulates through the collector, to potable water. (Figure by the author)

and the controller. The solar collector is protected against oxygen and minerals in the potable water so scaling and corrosion are not a problem. Scale may build up on the potable-water side of the heat exchanger but it may be removed with a chemical cleaning solution, and even if the heat exchanger needs to be replaced it is less expensive than the solar collectors. Still, having two pumps instead of one in general must increase maintenance. Freeze protection is provided by the concentration of the propylene glycol in the heat-transfer fluid. A simple indirect system may overheat if there is no hot water use for a long period of time or if flow through the collector is interrupted for any reason.

WARNING

Protection Against Freezing

One problem plaguing the very early solar industry was freezing. Even in warm climates a rare freeze can have ruinous consequences for a solar system and the company that installed it. Water expands as it freezes, and the increase in volume causes the pipe to rupture as the freezing occurs, as shown in Figure 4-15. Some say that the ice forms a piston that compresses the liquid water causing the pipe to break at its weak point, but I have also seen ice right there at the break.

Multiple strategies have been used to prevent freeze damage:

- Antifreeze solution. The most common way to forestall freezing is to use a heat-transfer fluid that freezes at a very low temperature, such as –34C (–30F) for a 50 percent propylene glycol/water solution. Heat from this solution would be transferred to potable water within the heated building by a heat exchanger.
- Drain back. The fluid may be drained out of a collector when freezing is likely as in a drain-back schematic. Both of these strategies may be used together, so that any fluid trapped in the collector of a drain-back system will be protected by anti-freeze.
- Recirculation. Hot water from the storage tank may be circulated to the collector when freezing conditions are imminent by the action of a pump and controller, although measurements indicate that even with well insulated collectors the resulting heat loss can be significant (Walker, Mahjouri, and Stiteler 2004).
- Proponents of air-heating solar collectors point out that air as a heat-transfer fluid would not be susceptible to freezing.

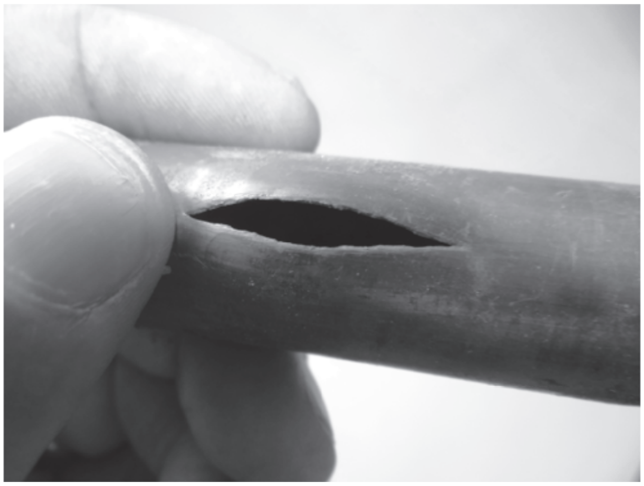

Figure 4-15. Photograph of 19 mm (3/4″) copper pipe burst by water freezing inside of it.(Photo by the author)

Indirect Active Solar Water Heating System Schematic with Coil-in-tank

It is possible to submerge a heat exchanger coil in the potable water tank and avoid the need for the second pump to circulate potable water, thus reducing initial cost and maintenance. However, the cost of a tank with a coil built into it is rather high and there are few suppliers, and it is even more expensive and hard-to-find with two coils, the upper one used for heating the tank from a conventional fueled boiler. This is the type of system that I have in my home. Because the potable water is on the outside of the heat exchanger tube, there is no flow blockage by scaling. Freeze protection is accomplished by the nonfreezing heat-transfer fluid. There is no specific protection against overheating of the collector loop. Such a configuration is illustrated in the schematic diagram of Figure 4-16.

Indirect Active Drain-back Solar Water Heating System Schematic

At times when the building is closed, or the occupants are away on vacation, the temperature of the solar storage tank will increase until the temperature sensor on the storage tank reaches a high-limit set in the controller, and the pump turns off. Under this condition the solar collector will continue to get hotter and hotter until the pressure relief valve opens and discharges fluid. This is undesirable since the pressure relief valve is a safety device, not a control device, and loss of heat-transfer fluid is costly and damaging. A drain-back tank built into the collector loop allows fluid to drain out of the collector whenever the pump stops, and thus provides protection against both freezing and overheating of the heat-transfer fluid. The schematic diagram of Figure 4-17 shows the position of the drain-back tank with the other system components.

The collector will reach its stagnation temperature sitting in the sun with no fluid circulating through it, but the materials from which the collector is built should be able to survive such stagnation conditions. I first saw this schematic on a school in Phoenix, Arizona, which closed in the summer, and it functioned so reliability that I've recommended it ever since. The drain-back system thus has built-in protection for both freezing and overheating—but the piping has to configured to drain back to the tank without trapping heat-transfer fluid in the collectors. Added reliability is obtained by charging this loop with a nonfreezing heat-transfer fluid with corrosion inhibitors, rather than just water.

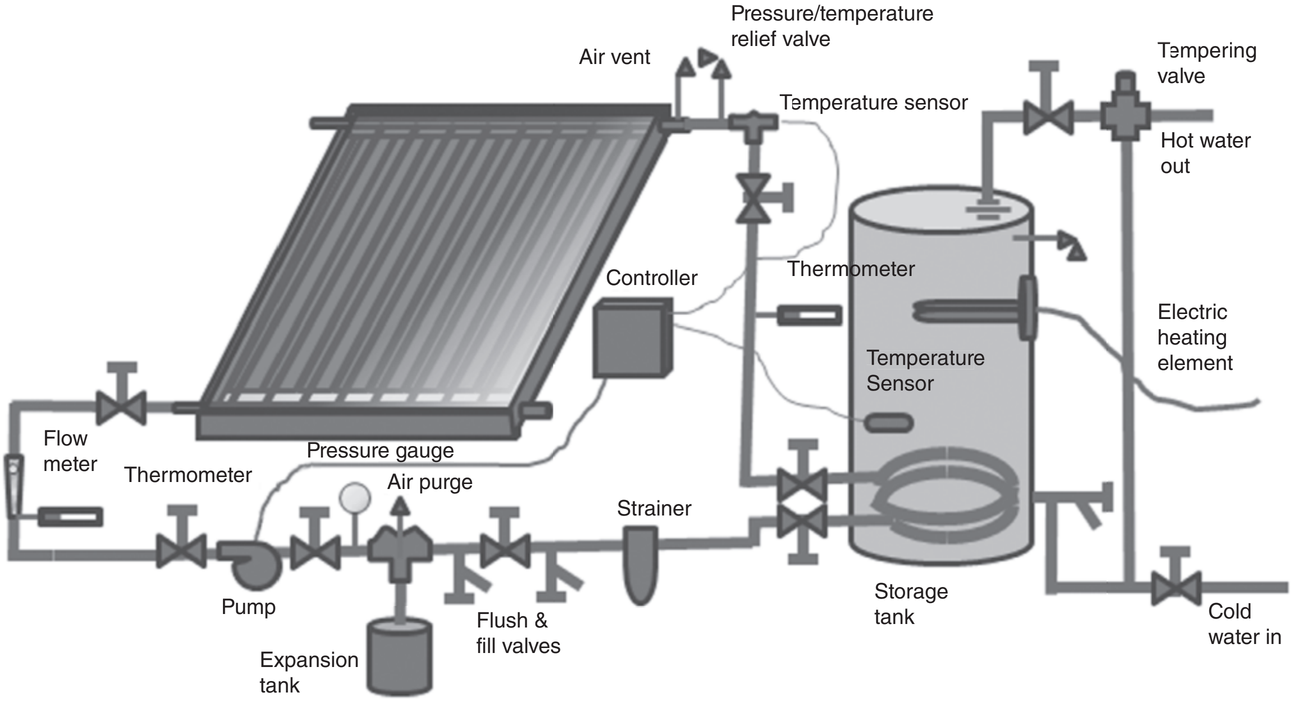

Figure 4-16. Schematic diagram of indirect active solar heating using coil-in-tank heat exchanger, which avoids the need for a second pump. (Figure by the author)

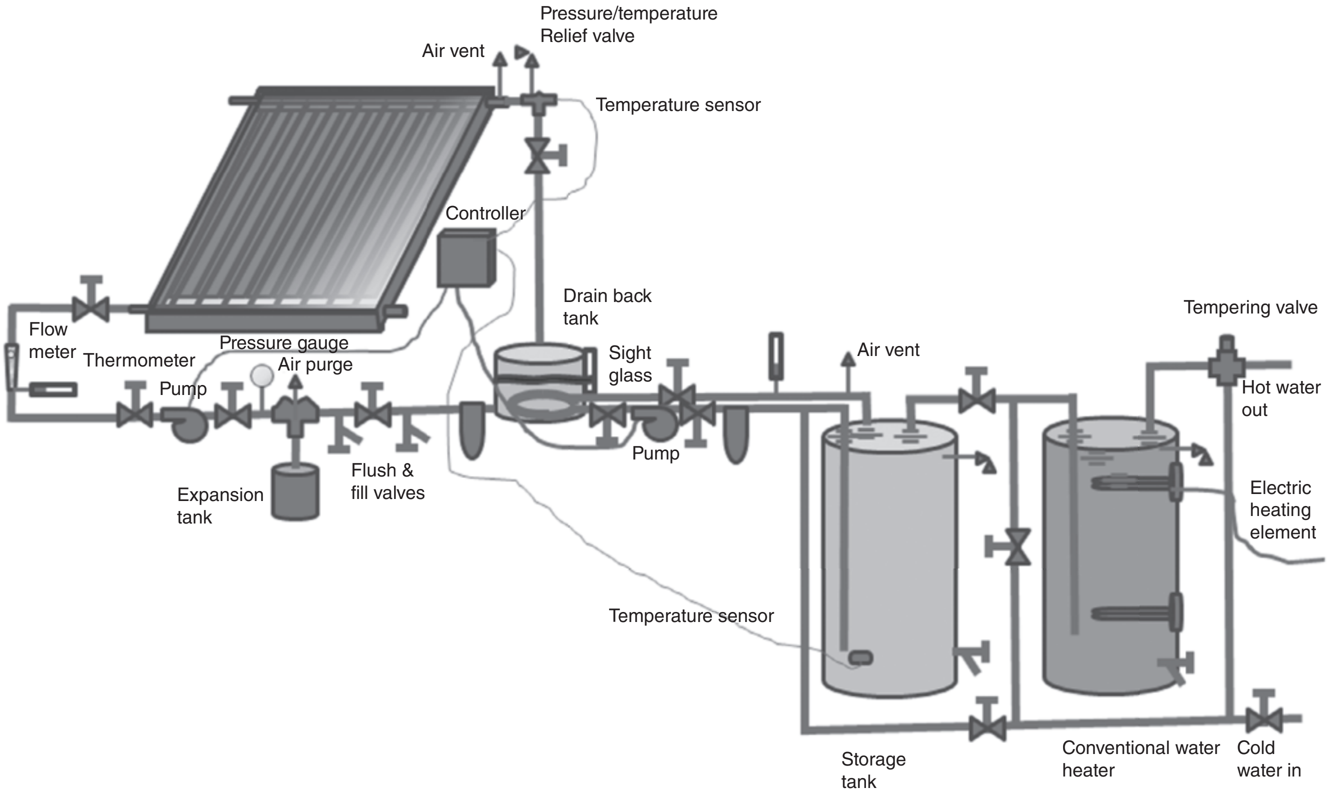

Figure 4-17. Schematic diagram of drain-back solar water heating system, in which the fluid drains from the collector when the pump is off, and using a coil in the drain-back tank to exchange heat to potable water. (Figure by the author)

WARNING

Protection against System Overheating

System overheating occurs when solar resources are sufficient but there is little or no hot water demand. It is especially common in space-heating systems in the summer. Several strategies for dealing with overheating have been developed:

- Drain back. The drain-back schematic offers a means of protection against overheating by allowing the fluid to drain back into a special tank or an oversized expansion tank when the pump is turned off by the high-temperature limit of the controller. The collector piping must be arranged so that gravity can push the fluid out pipes at the bottom of the collectors. If liquid is trapped in the collector by the shape of the piping or a check valve, then a high pressure will be maintained until all the liquid is boiled into vapor which will cause the pressure/temperature relief valve to discharge.
- Steam back. Another strategy to control overheating is to allow the high vapor pressure of the boiling, or almost boiling, fluid to push liquid down and out of the solar collector (and into the expansion tank). The dry collector will overheat, but not exceed pressure limits. The expansion tank would have to be sized to accommodate the internal volume of the solar collectors in addition to the thermal expansion of all the fluid in the system. This is called a “steam-back” design and also relies on plumbing that does not trap liquid in the collector.
- Stagnation pressure protection. “Pressure protection” is another strategy to deal with overheating. In this approach all the components of the system are specified to tolerate a relatively high pressure (say, 150 psi), and the system survives periods of high temperature and pressure without the pressure relief valve opening.
- Dump load. Finally, a controller may open a solenoid valve and dump hot water to drain when the storage tank overheats (above, say, 180F). At first, this sounds like a terrible waste of energy and water. But in fact it occurs very rarely, and when it does occur, it doesn’t take much water flow through the tank to cool it back down below the high-temperature limit of set on the controller.
- Air as heat transfer fluid. Note that use of air as the heat-transfer fluid between an air-heating solar collector and the storage tank also avoids these problems of overheating.

Direct Active Recirculation Loop Return Heating System Schematic

A building in Philadelphia issued a request for proposals for a solar water heater and got three responses. Two offerors proposed to run new piping up the eight-story building and utilize the indirect active heat exchanger schematic described above. The third offeror proposed to interrupt the building’s hot water recirculation loop in a penthouse on the roof, and impart solar heat to the water before it returns to the water heating plant in the basement of the building. Figure 4-18 shows a schematic diagram of such a configuration. This is a very simple

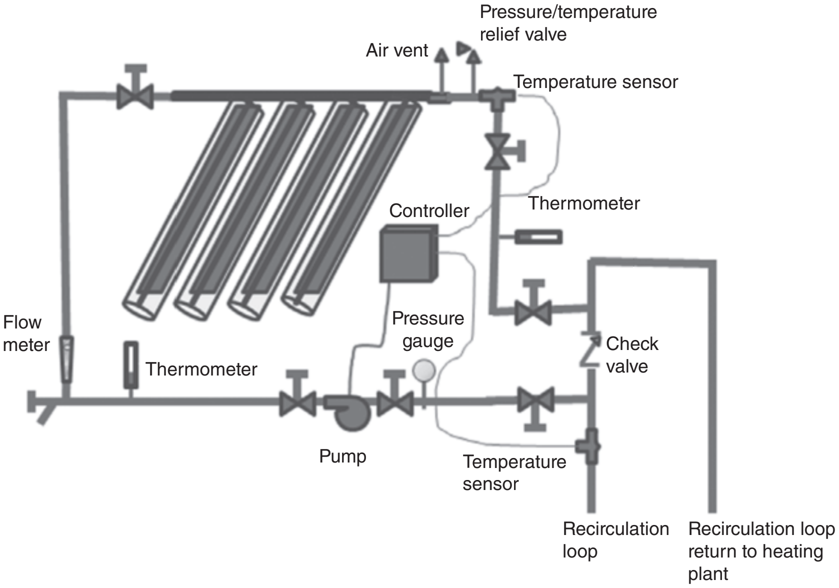

Figure 4-18. Schematic diagram of direct active solar hot water recirculation loop heating system, which imparts heat directly into the recirculating potable hot water loop of a building. (Figure by the author)

and elegant approach and avoids great expense of new piping through the building. However, since it has no additional storage, it depends on coincidence of the hot water use and the solar resource. This is good for only meeting up to, say, 40 percent of the hot water heating requirements, whereas the other system types can meet 70 percent, or higher fractions of the load. The recirculation loop itself is used as a source of heat to protect against freezing, but there is risk of freezing should the flow in the recirculation loop be interrupted. The controller is programmed to start the pump when the collector temperature sensor approaches freezing temperature, and hot water is circulated through the array until the collector temperature sensor reads a higher set temperature (Walker, Mahjouri, and Stiteler 2004).

SOLAR WATER HEATING SYSTEM COMPONENTS

We have discussed at length the types and characteristics of the solar collector, now we consider details of the other components that would make up a complete solar water heating system.

Collector Array

Multiple solar collectors may be "bussed" together by connecting the top and bottom manifolds, in effect connecting the riser tubes of the panels in parallel. Piping arrangements distribute the fluid to be heated to each such set of collectors in a "solar array". Collectors are often plumbed in parallel so that each collector has the coldest available inlet temperature, resulting in a high efficiency.

A piping arrangement called "reverse return" introduces water into the closest collector and then returns it from the farthest collector so that each collector sees the same (approximately) pressure drop across its riser tubes as shown in the piping arrangement of Figure 4-19. The same strategy can be used for the piping arrangement that distributes flow to each row of collectors, but then the length of additional piping becomes excessive and it is better to use balancing valves that can be adjusted to distribute flow evenly among rows. At least one balancing valve that would otherwise get the least flow in a system should be wide-open, and the others adjusted from that to evenly distribute the flow.

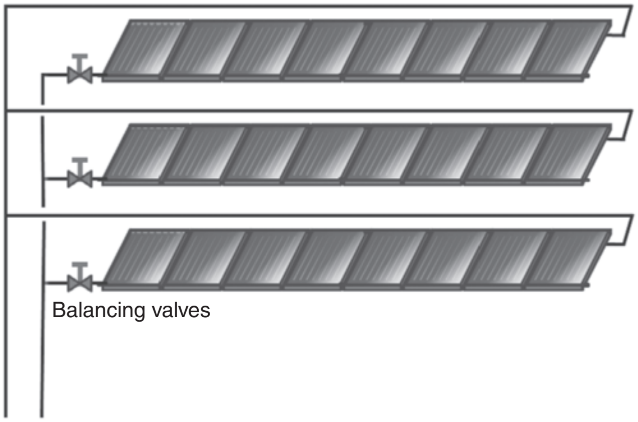

Figure 4-19. "Reverse return" piping is used to balance flow between collectors in a row, and "balancing valves" are used to distribute flow evenly among rows of collectors in parallel. (Figure by the author)

Splitting the flow between collectors in parallel reduces the flow rate through each one, reducing the heat removal factor, F_R. For liquid heating collectors, the effect of temperature and heat loss (U_l) is greater than that of heat transfer within the collector (F_R), so that plumbing collectors in parallel rather than in series is almost always recommended. For collectors that circulate air, the reduction of F_R with a reduced air flow rate is significant, but still collectors are often connected in parallel because fan power is excessive when collectors are in series. For well-insulated collectors the penalty of plumbing collectors in series is reduced, and in fact the evacuated absorber tubes of concentrating collectors are very often plumbed in a long series row along the focal line of the parabolic trough reflector.

Collectors in parallel introduce the problem of nonuniform flow through the array. One must consider not only static pressure, *P*, but the other terms in Bernoulli's equation, too, such as dynamic pressure $\rho V^2/2$. The sum of these two terms (static and dynamic pressure) is constant if we neglect other effects such as elevation differences. The static pressure forces flow through the riser tube closest to the inlet and outlet of the header, and "reverse return" plumbing is a strategy to separate the inlet and outlet so that pressure and resulting flow are uniform. However, the dynamic pressure tends to direct more flow to the downstream riser tubes, helping to balance the flow through an array. Flow is generally applied from bottom header to top header, so that if a riser tube is getting less flow and reaching a higher temperature, buoyancy of the heated fluid will increase rather than decrease flow through that riser tube.

It is possible to connect together six or eight solar collectors, depending on size, in parallel by connecting together the header manifolds of the collectors. Beyond that number, the flow is excessive for the header diameter, and piping must be supplied to another parallel row of solar collectors in order to increase the total area. Each such row is fitted with isolation valves to remove the row from service and balancing valves so that the flow can be evenly controlled among the rows.

Collector Mounting System

The forces acting on a solar collector include its weight, the weight of snow on top of it, and forces applied by wind. The roof mounting system must be able to accommodate the worst-case combination of these forces, and the building structure itself must be adequate to transmit these forces to the ground. Design of new construction would address these structural requirements, but in retrofit projects the structural adequacy of the roof trusses should be checked. Reinforcement of the underlying roof structure with blocking between rafters is often required. The trend in new construction is to design a roof only for design loads so no new loads may be added without reinforcement. Seismic forces are also a consideration in many locations. For photovoltaic panels, a shallow tilt or even flat on the roof may be a good mount, but for thermal collectors it is desirable to intercept more solar radiation in winter, when the sun is low in the sky, so a steep tilt angle is indicated (equal to local latitude, or steeper). Thus it is not possible to use aerodynamics to minimize wind forces in the same way that the design of a photovoltaic system may. Wind loads on evacuated-tube systems are reportedly less than those of flat-plate systems because air can blow between the tubes, and this characteristic has been taken advantage of in the design of ballasted systems, which are held in place by weighted blocks, rather than roof penetrations.

Solar collectors are mounted on the roof or on the ground, and in some rare instances on a vertical south wall. The feet of the supports must be connected to rafters, purlins, or columns and not only to the roof deck. A structural engineer must inspect the roof or roof plans, perform the loading calculations, and specify the type and number of fasteners for the loads (weight, wind) and allowable deflection. In some installations, the roof rack is ballasted with concrete blocks, and the weight of the ballast resists wind forces. For such ballasted systems, the roof structure must be strong enough to support the significant weight of the ballast blocks in addition to the weight of the rack, collectors, and other design loads such as snow.

In new construction, it is recommended that the architect design a section of roof with dimensions, tilt and orientation to accommodate the collectors flush on the roof. The photograph in Figure 4-20 shows such a configuration on a comfort station (showers and laundry) at Chickasaw National Recreation Area in Oklahoma.

Mounting systems for flush-on-roof consist of heavy-gauge aluminum or steel brackets, washers with a dish-shape to contain and protect sealant, bolts to penetrate the roof deck, and bolts to attach to the collector frame. Typically four brackets are used, two on each side of the collector. In extreme wind situations, or where required by local codes, two additional brackets are used. Brackets must be bolted securely to the building structure (rafters or joists). If a bracket falls between rafters, the underside of the roof must be accesses and “cats” or blocking fixed between the rafters.

Mounting systems for which the collectors are not flush on the roof will include all the above components plus a collector mounting frame truss and brackets to attach the truss to the collectors. The truss is usually constructed of aluminum angle or rectangular cross section. The tilt angle is adjusted by cutting the lengths of aluminum to the desired length in fabrication of the rack system.

Figure 4-20. Flat-plate solar collectors mounted flush on the roof of a shower and laundry facility at a campground in Oklahoma (Photo by the author)

Rail-mounting systems are specified when the roof is not accessible from the underside to make secure attachments and where roof penetrations are to be minimized. In rail-mount systems brackets at the base of the collector truss are mounted to a strong rail, and the rail attached at points where secure attachments are feasible.

Use blocking or spanners between rafters as illustrated in Figure 4-21. Figure 4-20 shows how solar collectors may be mounted flush on a roof, and render the appearance of a skylight, if the roof itself is at an acceptable angle and orientation.

A minimum spacing is required between the collector and the finished roofing. The gap required depends on location and local codes, but in general should be sufficient to allow water to drain and avoid the accumulation of debris such as leaves behind the collector.

For ground-mounted collectors, different types of foundations depend on the characteristics of the soil and have already been discussed in the chapter 3 (piles, caisons, footers),

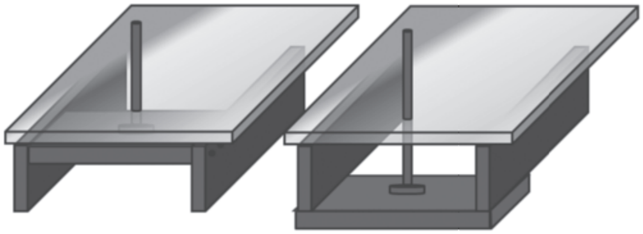

Figure 4-21. To avoid screwing a lag bolt hanger into a rafter or joist, consider a spanner (right) or blocking (left) between rafters of a roof. (Figure by the author)

(see Figure 3-18) and the same types would be considered for mounting solar water heating collectors. If mounted on the ground, safeguards such as fences are usually required to protect the public and to protect the array from theft or vandalism. One disadvantage of mounting on the ground is that more piping is required to connect to the building systems than roof-mounted system. This additional piping adds to the cost and thermal capacitance of the system. Heat loss from well insulated, buried pipe is not excessive, but the thermal capacitance exacts a heavy penalty as the system has to heat up before it can deliver useful heat and this is not recovered as it cools down at night.

Heat-transfer Fluid

In nonfreezing climates, such as Hawaii, it is common to circulate potable water through the solar collectors. Even a rare freeze causes copper pipes to burst, and many systems have been disabled by such leaks. So in general, a non-freezing heat-transfer fluid is circulated through the collector and the heat is transferred to the potable water by a heat exchanger. The most common heat-transfer fluid is a solution of propylene glycol and water. The solution would also include an alkaline buffer to compensate for the acidity of the glycol, and other additives to defeat mechanisms of degradation and corrosion. Specify fluid formulated for high temperature operation.

Compared to pure water, a propylene glycol solution would be more dense, have a higher viscosity, have a lower thermal conductivity, and have a lower specific heat. Thus pure water is the superior heat-transfer fluid except for the freezing problem. Whereas water freezes at 0°C (32.2°F), a solution of 50 percent propylene glycol and water would freeze at a temperature around –30° C (–21°F). Propylene glycol is nontoxic and is also used for winterizing shut-down drinking water systems, and is generally considered safe for applications where the used antifreeze eventually will be drained into water treatment or septic system. There are many manufacturers, including Dow Chemical.[4] Archer Daniels Midland makes propylene glycol as a by-product of manufacturing biodiesel fuel.[5] In bulk, propylene glycol sells for about $1,500 to $2,500 per ton; in small quantities, $15/gallon.

Pumps

Centrifugal pumps are usually used for solar water heating systems. In terms of solar collector performance, analysis indicates that maintaining the recommended flow rate is better than variable speed flow, due to the heat transfer within the riser tubes. However, in terms of overall system performance, a flow rate lower than the recommended flow rate enhances stratification in

REFERENCE

Properties of 50 percent Propylene Glycol, 50 percent water solution at 300K (81F)

Properties of a heat-transfer fluid solution change with composition of the fluid (percent propylene glycol) and the temperature. The heat-transfer fluid operates over a very wide temperature range from very cold –45C (–50F) to very hot to 160C (325F), and the properties may change by 10 percent or more over this range. However, empirical relationships are often correlated against the properties of fluid coming into a solar collector or heat exchanger, so here we consider properties at 30C (81F) as a typical temperature and list the properties in Table 4-6. A 50 percent concentration extends freeze protection to –34C (–30F). Properties are from DOWFrost HD product literature (msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0040/0901b80380040bcb.pdf?filepath=heattrans/pdfs/noreg/180-01314.pdf&fromPage=GetDoc). Properties depend on composition and concentration: consult literature from the manufacturer for the specific product considered.

TABLE 4-6. THERMOPHYSICAL PROPERTIES OF 50 PERCENT PROPYLENE GLYCOL; 50 PERCENT WATER SOLUTION AT 30 C (81F).

ρ	Density	1038 kg/m^3 (64.8 lbm/ft^3)
$\mathbf{c_p}$	Specific heat	3800.0 J/kgK (860 Btu/lbmF)
k	Thermal conductivity	0.4 W/mK (0.231 Btu/hrftF)
ν	Kinematic viscosity	4.34×10^{-6} m^2/s (0.168 ft^2/h)
β	Expansion coefficient	0.13000 1/K (0.00185 1/R)

WARNING

Safety and Protection of Potable Water

Solar water heating systems are often used to heat potable (drinking) water, and safety is of paramount importance in protection of the potable water from dangerous conditions. Water should be protected from chemical contamination by use of a nontoxic heat-transfer fluid and by use of a double-wall heat exchanger. Many industrial and automotive heat-transfer fluids are toxic—avoid those. Biological contamination is also a consideration and conditions that allow for agents such as Legionnaires' disease should be avoided by designing for temperatures high enough to prevent biological growth in the water. If storage requirements indicate a large storage tank, consider a load-side heat exchanger as a means of avoiding a large volume of warm potable water. Following installation, all system components in contact with potable water should be disinfected according to standard guidelines. A tempering valve is needed to avoid delivery of dangerously hot water.

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[4] See www.dow.com/propyleneglycol/ (Accessed March 2013).

[5] See www.adm.com/en-US/products/evolution/Propylene-Glycol/Pages/Manufacturing-Facility.aspx (accessed March 2013).

the storage tank so that colder water is returned to the collector and efficiency is increased due to less heat loss. Also in terms of overall system performance, it may be wise to use a lower flow rate to heat a lower volume of water to a higher temperature, and thus be ready for a user of hot water to make a draw without having to use the conventional source of heat. Here we consider single speed pumps, and then consider the application of variable speed pumps.

The body of the pump, and the pump volute, are made of cast iron, bronze, or stainless steel. Cast iron is used only in closed loops which control the corrosive aspects of the fluid. For systems that circulate potable water or that are open to introduce new oxygen, the bronze or stainless steel pumps would be indicated. Within the pump, an electric motor spins an impeller attached to its shaft. Fluid in the impeller is accelerated to the perimeter, where it is scraped off the impeller by an edge in the volute and the kinetic energy is converted to fluid pressure by the shape of the volute (the shape of a diffuser). In low-head, high-flow pumps, the blades of the impeller are short and wide, like the shape of a cylinder. For high-head, low-flow pumps the impeller blades are long and narrow, so the impeller has a shape like a flat disk. Either is driven by the same speed motor, say 3,250 or 3,600 rpm. In so-called “cartridge pumps” the impeller and rotor are fabricated into a replaceable cartridge, without replacing the pump body or motor. Motors are often of the split capacitor type. The starting capacitor and wiring connections are in a box mounted on the motor body. Figure 4-22 shows a circulating pump quite common in solar water heating systems.

The pump operating condition is a combination of flow rate and resulting pressure drop around the fluid circuit. The pressure drop is the sum of pressure drop through each component and the length of connecting piping. Some schematics circulate potable water through a single collector loop, and have only one pump. Others have one pump circulating a loop of nonfreezing fluid and a second pump circulating a loop of potable water. But in all cases it is a matter of adding up the pressure drop through each fluid loop (circuit), and selecting a pump by referring to pump curves of flow and pressure.

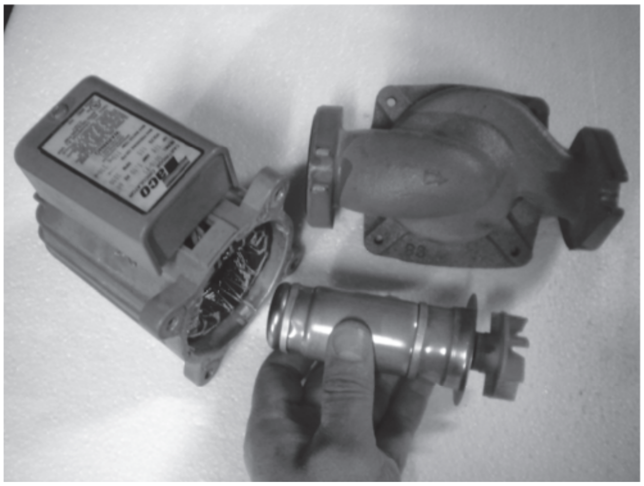

Figure 4-22. A centrifugal cartridge pump commonly used in solar water heating systems. (Photo by the author)

Start at the pump outlet and add up the pressure drop of each component all the way around the fluid circuit loop back to the pump inlet. Each component along the way has a pressure drop associated with it, and there will be a pressure drop due to the entire length of loop piping. The pressure drop is calculated from the flow rate and the frictional property of the component. The sum of all these pressure drops is the pressure, or hydraulic head, that the pump must impart to the fluid to overcome friction at the desired flow rate. For example, consider a water heating system that had two loops, one circulating a nonfreezing heat-transfer fluid and the second circulating potable water, the pressure drop around the solar collector loop would be

$$\Delta P_{\text{pump, collector loop}} = \Delta P_{\text{collector}} + \Delta P_{HX} + \Delta P_{\text{Piping}} + \Delta P_{\text{Buoyancy}} + \Delta P_{\text{Elevation}} \tag{4-26}$$

And the pressure head required of the loop circulating the potable water would be

$$\Delta P_{\text{pump, loop}} = \Delta P_{\text{Tank}} + \Delta P_{HX} + \Delta P_{\text{Piping}} + \Delta P_{\text{Buoyancy}} + \Delta P_{\text{Elevation}} \tag{4-27}$$

The standard rating procedure reports the pressure drop through the solar collector, $\Delta P_{\text{collector}}$, at three different flow rates specified by the testing procedure. The manufacturer’s literature always lists the pressure drop at the manufacturer’s recommended flow rate. One of these four is usually pretty close to the flow rate specified for your project. If not, you may interpolate by pasting the three values of pressure drop and flow into a spreadsheet program and fit to a second-order curve to find out the pressure drop at any flow rate. For example, Table 4-7 lists the pressure drop as reported by the standard testing procedure for a glazed flat-plate solar collector.

Similarly, the heat exchanger manufacturer’s literature will include charts of pressure drop across the heat exchanger, ΔP_{HX}, for different flow rates, or if tables they may be interpolated using a quadratic curve fit.

TABLE 4-7. PRESSURE DROP AT EACH OF THREE FLOW RATES REPORTED IN STANDARD TEST OF SOLAR WATER HEATING COLLECTOR

Flow		ΔP	
ml/s	(gpm)	Pa	(in H_2O)
20	(0.32)	28	(0.11)
50	(0.79)	115	(0.5)
80	(1.27)	256	(1.03)

The pressure drop through the length of piping and each plumbing fitting, including the tank transitions, is calculated at any flow rate using a dimensionless friction coefficient, *f*, known as the Darcy friction factor. This factor is multiplied by dynamic pressure in the equation for pressure-drop, the Darcy Weisbach equation:

$$\Delta P_{\text{pipe}} = f\frac{L}{D}\left[\frac{1}{2}\rho V^2\right] \tag{4-28}$$

where
L is the length of pipe (m)
D is the diameter of the pipe
f = is the dimensionless friction coefficient depending on the Reynolds number of the flow through the pipe and the surface roughness of the pipe.

The pressure drop of the fluid transitioning from the pipe to the tank, and again from the tank back into the pipe, ΔP_{Tank}, may be calculated using a friction factor times dynamic pressure and appears the same as a plumbing fitting in the summation. For the pipe itself, the value of the friction coefficient, *f*, is found on a chart called the “Moody” chart, which may be found in any fluid engineering reference book or textbook. For laminar flow, the theoretical relationship for laminar flow in a duct of circular cross section is $f = 64/\text{Re}$ and is shown on the Moody Chart as a straight line dropping from $f = 0.064$ at $\text{Re} = 1000$ to $f = 0.016$ at $\text{Re} = 4000$. Then, for turbulent flow, the Moody Chart shows the friction factor dropping from 0.04 at Re = 3000 to 0.01 at Re = 3 million along a syncline curve.

The Reynolds number used in the Moody Chart is calculated as average velocity in the pipe, V (m/s, ft/s), multiplied by pipe diameter, D (m, ft), and divided by kinematic viscosity of the fluid, ν. Kinematic viscosity is absolute viscosity, μ (Ns/m^2, cP), divided by density, ρ (kg/m^3, lbm/ft^3). The pressure drop associated with any other features of the piping such as valves, elbows, and the tank inlet and outlet also have friction factors associated with them that are tabulated in the fitting manufacturer’s literature and would be included in a summation of pressure drop around the loop. Each of these fittings including the tank can be expressed as equivalent lengths of pipe and added in the equation for pressure drop through the pipe length in order to calculate the total pressure drop associated with the pipe length L and all of the pipe fittings.

$$\Delta P_{\text{piping}} = f\left[\frac{L}{D} + K_{\text{tank in}} + K_{\text{tank out}} + K_{\text{elbow}} + \cdots K_N\right]\left(\frac{1}{2}\rho V^2\right) \tag{4-29}$$

Where “...K_N” means keep adding up all the fittings that occur along the loop circuit until you’ve accounted for every fitting.

Some K values are listed for example in Table 4-8. For a complete list of the K values consult the suppliers of the pipe fittings, but typical values of K are listed here for the fittings most often found in a solar hater heating system (Winn et al. 1980):

TABLE 4-8. VALUE OF FRICTION FACTOR, K, FOR EACH TYPE OF FITTING

Pipe into tank	K = 0.5
Pipe out of tank	K = 1.0
Gate valve	K = 8
Swing check valve	K = 100
Straight through T fitting	K = 20
Turn at T fitting	K = 60
90-degree elbow	K = 30
90-degree extended radius elbow	K = 15
45-degree elbow	K = 16

Example Calculation of Friction Pressure Drop

In this example we calculate the frictional pressure drop around a closed loop consisting of 24 solar collectors plumbed in parallel, a heat exchanger to transfer heat to potable water, connecting pipe, and associated fittings. The pressure drop across each collector, and across the bank of solar collectors connected in parallel, is 220 Pa (0.88 in H_2O) at the recommended flow rate of 0.08 l/s (1.3 gpm) per collector according to the manufacturer’s literature. There is 50 feet of 1-inch diameter pipe that runs to each row of 8 collectors, accommodating a flow rate of 0.64 l/s (10 gpm). Each of these collector bank piping loops also contains two valves (for balancing flow between the banks and to shut off a bank from the rest of the system), and two 90-degree elbows. The rest of the loop consists of 100 feet of 1 1/2-inch pipe which combines the flow of from all three collector banks for a total flow rate 1.95 l/s (30 gpm). This 1 1/2 inch-diameter pipe includes two ball valves (one on each side to isolate the pump), one gate valve (to separate the flush and fill valves), two straight-through tees, four 90-degree elbows, a strainer, and a heat exchanger. At this total flow rate the pressure drop across the heat exchanger is 21 kPa (3 psi) and that across the strainer is 7 kPa (1 psi) according to a chart in the manufacturer’s literature.

Since we are given the pressure drop across the collector, heat exchanger and strainer by the manufacturer’s literature, we need only calculate the pressure drop through the piping system.

For the 1-inch diameter pipe to each collector bank, and for the 1-1/2 inch pipe to the heat exchanger, the pressure drop is calculated in the Table 4-9.

The pressure drop of the 1-inch pipe is the same across all three collector banks. We do not add together the pressure drops of three rows in parallel; rather the pressure drop is the same and the flow adds. We do, however, add up the pressure drops across all the components in series to arrive at the total pressure drop of the system.

Thus, as detailed in Table 4-10, the pump must overcome a frictional pressure drop of 63 kPa (9.1 psi) at the flow rate of

TABLE 4-9. EXAMPLE CALCULATION OF PRESSURE DROP THROUGH EACH BANK OF SOLAR COLLECTORS AND FOR THE BALANCE OF SYSTEM

	Each collector bank	**Piping from collector to heat exchanger**
Pipe diameter, d	0.025 m (1 Inch)	0.038 m (1.5 Inch)
Volume flow rate, V	0.65 l/s (10.3 Gpm)	1.95 l/s (30.9 Gpm)
Velocity, v = (4*V/1000)/ (3.14159*(d^2))	1.28 m/s (4.2 ft/s)	1.71 m/s (5.6 ft/s)
Reynold's number, Re = vd/ν	7508	15015
Friction factor, f	0.034	0.034
Dynamic pressure 1/2 ρV^2	427.02 Pa (.062 psi)	759.15 Pa (0.110 Psi)
Length of 1″ pipe	15.24 (50 ft)	30.49 (100 ft)
L/d	600.15	800.20
3 Valves (K = 8)	24	16
4 90 degree elbows (K = 30)	120	60
2 Straight-through tees (K = 20)	0	40
$\Delta P_{piping} = f$[(L/D)+ K_valve + K_{elbows}] (1/2 ρV_^{2})	10.804 kPa (1.57 Psi)	23648 kPa (3.43 Psi)

1.95 l/s (31 gpm). To this we would add any other sources of pressure drop, such as gravity and buoyancy (in this example we neglect gravity since it is a closed loop, and neglect buoyancy because the collectors and heat exchanger are on the same elevation). The pump selection process is one of finding a pump with its maximum efficiency near the intersection of pressure drop and flow rate on the pump curve.

TABLE 4-10. EXAMPLE CALCULATION OF PRESSURE DROP OF COMPONENTS IN SERIES—EACH ADDS TO DETERMINE THE TOTAL PRESSURE DROP AT A GIVEN FLOW RATE

Component in series	**Pressure drop**
1 inch piping	10.80 kPa (1.6 Psi)
1.5 inch piping	23.65 kPa (3.4 Psi)
Solar collectors	0.22 kPa (0.0 Psi)
Heat exchanger	21.00 kPa (3.0 Psi)
Strainer	7.00 kPa (1.0 Psi)
Total pressure drop	62.67 kPa (9.1 Psi)
Total flow rate	1.95 l/s (30.9 Gpm)

If the collector loop is not closed nor entirely filled with fluid, then the pump power will have to elevate the fluid over a height difference. For example, if the pump takes the water out of an open tank and pumps it up to the collector. So called "drain back" systems which allow the water to settle back into a drain-back tank will also require enough head pressure to push the fluid back up to the collector when the pump starts.

$$\Delta P_{elevation} = \rho_{cold} g h_{pipe} \tag{4-30}$$

Where g is acceleration due to gravity which has a value of 9.8 m/s^2 or 32.2 ft/s^2 and h_{pipe} is the vertical distance spanned by the pipe. For closed, pressurized systems, the elevation head is the same on both sides of the pump and this term may be neglected.

Finally, buoyancy occurs because of a difference in the fluid density between the solar heated fluid coming down, ρ_{hot}, versus the density of cold fluid going back up to the solar collectors on the roof, ρ_{cold}. The pump power must be sufficient to overcome the pressure difference resulting from buoyancy, $\Delta P_{buoyancy,}$ in addition to the other pressure drops, and force the hot fluid down. Pressure difference due to buoyancy in the pipe is:

$$\Delta P_{bouyancy} = (\rho_{cold} - \rho_{hot}) g h_{pipe} \tag{4-31}$$

For a solution of 40 percent propylene glycol and water, the density would change from ρ_{hot} = 1005 kg/m^3 at 60C to ρ_{cold} = 1020 kg/m^2 at 40C, for a difference of around 15 kg/m^3. The volumetric expansion coefficient for a propylene glycol solution gives the percent change in density with temperature and is listed with other properties in the sidebar.

Finally, the pressure head required of the pump is the sum of the pressure drop associated with each of these effects. In order to conserve pump power, each of these terms should be minimized. Strategies to minimize pump power include oversizing the pipe by one size and using only extended radius elbows where possible. However, pressure drop associated with heat transfer in the solar collector and the heat exchanger is inevitable. The equations for heat transfer based on thermal conductivity and temperature of the fluid are almost identical to the equations for friction based on viscosity and velocity of the fluid. In an analogy known as Reynolds' Analogy, the frictional pressure drop will be proportional to the heat transfer, and this offers another way to estimate required pump power before the details of the design are sufficient to use the method described above. The constant of proportionality depends on the fluid properties and the temperature involved, but for water and a 10°C (20°F) temperature difference is on the order of 0.02. For example, to transfer 1,000W of heat would involve at least 20 W of pump power.

We know the fluid flow rate from the manufacturer's recommendation for the solar collector, or from more detailed optimization. Based on that flow rate, we calculated the pressure drop around the piping loop. Based on this flow rate and associated pressure drop, we can specify the pump. In order to select a

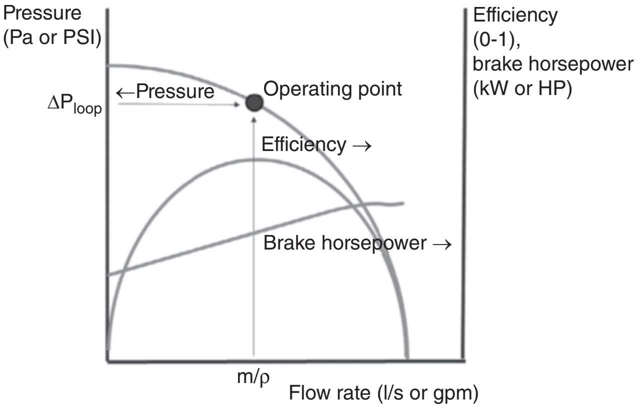

Figure 4-23. Conceptual performance curve for a centrifugal pump. We seek to select a pump which has an operating point close to the maximum efficiency of the pump for a given pressure drop and flow rate through the piping system. (Figure by the author)

pump, it will be necessary to refer to the "pump curve" for each pump to be considered. Figure 4-23 is a conceptual representation of what most pump curves look like.

The volume flow rate is the mass flow rate, m, divided by the density of the fluid entering the pump, ρ_{cold}. Indicate your volume flow rate and pressure drop on the performance curve for each pump being considered, and select the pump with a maximum efficiency closest to the desired operating point of pressure and flow. You want to achieve a certain flow rate, m, and that flow results in the pressure drop around the plumbing loop $\Delta P_{loop,}$ so you just have to keep looking at different pump curves until you find one that has its maximum efficiency near your operating point of volume flow rate and pressure.

To size the electric motor to drive the pump, read the brake horsepower from the pump performance curve at the operating point and divide by the electric motor efficiency. The brake horsepower is the power imparted to the fluid divided by the pump efficiency. The power imparted to the fluid is the volume flow rate multiplied by the pressure difference.

$$P_{motor} = \frac{m\Delta P_{loop}}{\rho_{cold}\eta_{pump}\eta_{motor}} \tag{4-32}$$

Where P_{motor} is the electric power consumption of the pump motor

η_{pump} is the pump efficiency, and

η_{motor} is the efficiency of the electric motor.

The energy required to provide this power over a year would be

$$Q_{pump} = P_{motor} \times \frac{\text{hours}}{\text{day}} \times \frac{\text{days}}{\text{year}} \tag{4-33}$$

Considering that it may take a few hours for the solar collectors to heat up in the morning, the pump might run an average of 10 hours per day depending on conditions.

Example Calculation of Pump Power Requirements

Consider the friction calculation from the example above with three rows of 8 collectors each plumbed in parallel. The result of that calculation was that the pump must overcome a frictional pressure drop of 63 kPa (9.1 psi) at the flowrate of 1.95 l/s (31 gpm). For this example assume that the collector loop is closed and that elevation differences are negligible, so this frictional pressure drop is the only pressure that the pump needs to overcome. Assume for this example that the pumps we are considering are around 60 percent efficient, and that the electric motors are around 85 percent efficient. Recognizing that the density of water is approximately 1 kg/l and 1 l = 0.001 m^3, and also recognizing that 63 kPa = 63000 N/m^2, the above equation for pump power becomes

$$P_{motor} = (0.00195 m^2/s)(63000 N/m^2)/(0.50)/(0.85) = 293 W$$

Strainer

A strainer is a screen that protects the pump from objects that may jam the impeller. Although frequently omitted in system design, it avoids the possibility of a blob of solder jamming the pump—ask me how I know this.

Heat Exchanger

In nonfreezing climates such as Hawaii, potable water is often circulated directly through the solar collectors. However, in climates where freezing is a possibility, a nonfreezing fluid such as a solution of propylene glycol and water is circulated in a "closed loop" through the collector and the heat is transferred by means of a heat exchanger to the potable water. There are other advantages to a closed-loop system, such as avoiding corrosion due to dissolved oxygen in potable water and avoiding scaling from minerals in potable water. Corrosion and scaling would still occur on the side of the heat exchanger that circulates potable water, but the heat exchanger is much easier to clean or replace than the solar collectors. In systems that circulate air through the solar collectors, a heat exchanger made of finned coils would transfer heat to the potable water from the solar heated air.

Of the different geometries and flow configurations available, counterflow compact heat exchangers are most commonly used in solar liquid heating systems. Counterflow allows the temperature of the potable water leaving the heat exchanger to approach that of the hot fluid from the solar collector entering the heat exchanger. In fact, if the heat exchanger were infinitely large, the fluid to be heated would exit the heat exchanger at the same temperature as the hot fluid coming in. This ideal rate of heat transfer is

$$q_{ideal} = (mc_p)_{min}\,(T_{hot,in} - T_{cold,in}) \tag{4-34}$$

Where $(mc_p)_{min}$ is the minimum of the two capacitance flow rates, that of the hot water flowing in the collector loop and that of the cold potable water in the storage tank loop. Capacitance flow rate is the mass flow rate (kg/s) times the capacitance (kJ/kgK), and thus has units of kJ/s/K or kW/K. The lesser of the two capacitance flow rates $(mc_p)_{min}$ limits the heat transfer. The greater of the two is given the symbol $(mc_p)_{max.}$

The actual heat transfer is calculated based on the decrease in the temperature of the hot fluid or the increase in the temperature of the cold fluid. Neglecting heat loss off the heat exchanger itself and heat generated by viscous friction, the two should be equal.

$$\begin{aligned} q_{\text{ideal}} &= (mc_p)_{\text{cold}}\,(T_{\text{cold,out}} - T_{\text{cold,in}}) \\ &= (mc_p)_{\text{hot}}\,(T_{\text{hot,in}} - T_{\text{hot,out}}) \end{aligned} \tag{4-35}$$

The trouble with Equation 4-35 is that neither $T_{\text{cold,out}}$ nor $T_{\text{hot,out}}$ are known. The heat exchanger effectiveness is defined as the ratio of actual heat transfer rate to this ideal heat transfer rate.

$$q_{\text{actual}} = e_{HX}(mc_p)_{\text{min}}\,(T_{\text{hot,in}} - T_{\text{cold,in}}) \tag{4-36}$$

Incropera and Dewitt (Incropera & DeWitt, 2005) give the effectiveness for a counter-flow heat exchanger as:

$$e_{HX} = \frac{1-e^{-NTU\left[1-\frac{(mc_p)_{min}}{(mc_p)_{max}}\right]}}{1-\frac{(mc_p)_{min}}{(mc_p)_{max}}e^{-NTU\left[1-\frac{(mc_p)_{min}}{(mc_p)_{max}}\right]}} \tag{4-37}$$

Where NTU is the "number of transfer units" equal to

$$NTU = UA_{HX}/(mc_p)_{\text{min}} \tag{4-38}$$

Where A_{HX} is the area of the heat-transfer surface within the heat exchanger and U is the overall heat-transfer coefficient, including convection on both sides and conduction through the metal separating the two streams. For shell and tube heat exchangers made of metal, the U value is on the order of 80 to 100 Btu/hr/ft^2/F. The UA_{HX} is essentially constant, depending mostly on the geometry and materials of the heat exchanger, and is published in the manufacturer's literature for a given model of heat exchanger, but it does also vary depending on the properties and temperature of the fluid. Figure 4-24 is a photograph of the end of a shell-and-tube heat exchanger showing both flow passages.

So called "compact" heat exchangers have thin stainless steel plates and narrow flow passages that are only about 1 mm wide, the same thickness as the thermal boundary layer within the fluid, resulting in a very effective heat transfer within a small package. Compact heat exchangers may be brazed or welded, the welded having the advantage of being only one material.

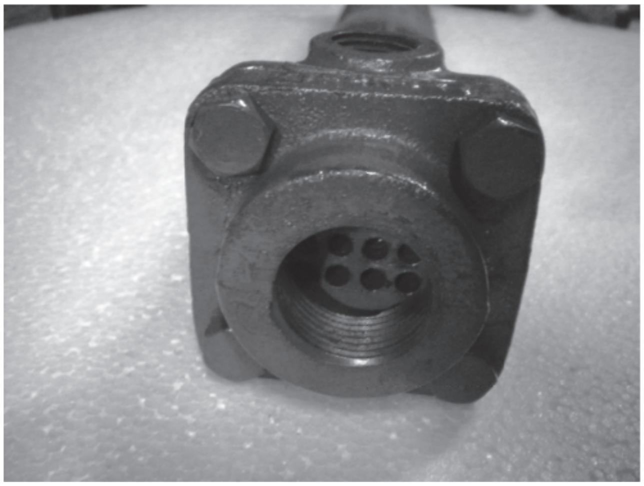

Figure 4-24. Shell-and-tube heat exchanger. Solar fluid usually flows inside the small tubes with potable water flowing through the shell external to the tubes. (Photo by the author)

Effectiveness equations for different geometries and flow arrangements of heat exchangers may be found in a good heat-transfer textbook, such as Incropera and DeWitt's *Fundamentals of Heat and Mass Transfer* or reference book. But perhaps the best resource for heat-exchanger effectiveness is the graphs and equations provided by the manufacturers.

The heat exchanger should be mounted as close to the storage tank as possible to minimize the pressure drop, heat loss, and capacitance of the connecting piping. Very small heat exchangers, called "side arm" heat exchangers are hung on the side of the tank and use natural convection to circulate the potable water. But in general, heat exchangers must be well supported because they are heavy. The outside shell of the heat exchanger, and even the supporting brackets, should be well insulated, as should the connecting piping.

The International Building Code and other standards require "double-wall" heat exchangers, so that if nonpotable heat-transfer fluid leaks out, it will be detectable instead of leaking into the potable water. A double wall is created by slipping a tube into a larger tube and bridging the gap between the two with fins radiating out of the inner tube. A double-wall heat exchanger has a lower U-value, so will be larger to get the necessary UA value. A double-wall heat exchanger is also created by two separate coils submerged in a tank.

The U-value of a heat exchanger created as a coil in a tank is typically on the order of 600 W/m^{2}C (Beckman and Duffie 2006). The cost of a water-to-water heat exchanger is on the order of \$1/kBtu/hr; and for a water-to-air heat exchanger cost is on the order of \$4/kBtu/hr.

Controller

The necessary controls for a solar water heating system are very simple, but may include more advanced features for monitoring and diagnostics. For residential systems a stand-alone controller is used, but even in commercial systems it is common to find a stand-alone controller controlling the solar water heating system, and the building energy management and control (EMCS) system being used only for monitoring. The type of control system used for solar water heating systems is a "delta T" controller, referring to control based on a temperature difference. The controller consists of a comparator and relay circuit that subtracts the resistance of a thermistor mounted on the bottom of the storage tank from one mounted on the collector outlet. A thermistor is a sensor, the electrical resistance of which varies with temperature. If the temperature of the collector is hotter than that of the storage tank by a set amount, the pump turns on. If this temperature difference drops to below a set amount, the pump turns off. For some controllers these set-points are fixed by the resistance of two resistors in the circuit, but for most they are adjustable using potentiometers in place of the resistances. Figure 4-25 shows the position of the potentiometers in a simple comparator circuit often used to control the pumps of a solar water heating system. Default settings are 6 C (12F) on and 2C (4F) off. Another function of the controller is to turn the pump off when the temperature of the tank approaches 85 C (180 F) in order to avoid overheating of the potable water tank. For many years, a product called "Morningstar" dominated the controller market, and in more recent years suppliers of collectors or complete system have branded their own controllers. Many of these have more advanced features, such as display of system status and temperatures. Some even record data over time and display it on a small screen. Since the flow rate through the collector loop is essentially constant, it is possible to multiply this calibrated mass flow rate by the temperature difference and display and record delivered energy. Most controllers simply turn the pump on or off with a relay, but proportional controllers and variable speed pumps are available. Analysis indicates that a fixed flow rate, at the manufacturer's recommended flow rate, optimizes collector performance, but a new trend is to optimize flow rate based on overall system performance, resulting in much lower flow rates than manufacturer's recommendation. This is due to maintaining stratification in the storage tank, so that the coldest water available is sent to the collector, thus maximizing collector efficiency, and due to the hotter water being returned from the collector being hot enough for a load draw should someone use hot water in the building.

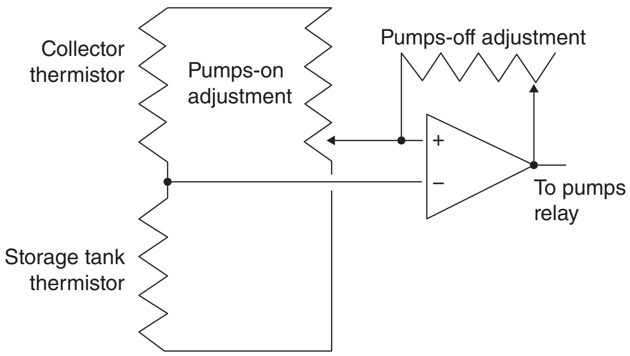

Figure 4-25. Diagram of "comparator" circuit typically used to control pumps of a solar water heating system. (Figure by the author)

Storage Tanks

For commercial buildings where the water use is during the day, a solar system may provide 20 percent or perhaps as much as 40 percent of the energy without storage by adding heat to the recirculation loop. But for most residences where hot water use is in the morning and evening—and for most commercial buildings as well—storage is needed to match the intermittent solar resource to the load. Sensible heat storage systems store energy by an increase in the temperature of a mass. The amount of energy stored per unit temperature increase is the specific heat of the storage medium.

$$q_{\text{stored}} = M_{\text{storage}} C_{p,\text{storage}} \frac{dT_{\text{storage}}}{dt} \tag{4-39}$$

Where M_{storage} is the mass of the storage medium (kg or lbm), $C_{p,\text{storage}}$ is the specific heat (kJ/kg/K or Btu/lb/F), and $dT_{\text{storage}}/\text{dt}$ (C/s or F/hour) is the rate at which the temperature is increasing. If the tank is heating up, dT/dt is positive, if the tank is cooling down, dT/dt is negative. Over a period of time, the amount of energy stored is

$$Q_{\text{stored}} = M_{\text{storage}} C_{\text{p,storage}} \Delta T_{\text{storage}} \tag{4-40}$$

Where $\Delta T_{\text{storage}}$ is the temperature at the end of the period of time minus the temperature at the beginning of the period. From this equation we can deduce some important characteristics of any sensible heat storage system. First, we note that storage capacity is proportional to the mass involved, so sensible storage systems are big and heavy. Storage is also proportional to temperature increase, so if we want to maintain a constant temperature, such as we would in a swimming pool or spa, that mass may not be used as storage. In fact, we want to allow the storage tank to get as hot as possible in order to store more heat in the same mass. So materials must be able to tolerate high temperatures, and drastic changes in temperature, and still maintain a long useful life. Very high temperature water may not be delivered to users, so it would be mixed with cold water in the tempering valve, and this increases the volume of the water delivered to the load beyond that drawn from storage. Finally, we desire a material with a high specific heat to reduce the mass involved. Water is an excellent storage medium because it has a high specific heat, good heat-transfer properties, and is universally available. The specific heat of water is around 4.2 kJ/kg/K but varies slightly with temperature. In IP units, the specific heat of water is 1 Btu/lbm/F, which is the definition of the British thermal unit, Btu: the amount of energy to raise one pound of water by one degree F. By comparison, the specific heat of rock is about 0.8 kJ/kg/K, significantly less than that of water.

Phase-change materials (PCMs) store heat through a change of phase rather than a sensible temperature increase and offer an advantage for solar systems because they allow the collector to continue to operate at a lower temperature and higher efficiency as heat is stored. The change of phase also stores a large amount of heat so less mass is required. The two types of PCMs suitable for solar energy systems are salt hydrates and organic materials. Salt hydrates store heat as water is liberated from a crystalline salt structure and as heat is removed from the media the water is reabsorbed. The temperature at which this phase change occurs may be adjusted by the selection of the salt chemistry and the concentration of water. Suitable salt-water mixtures have the same composition in the liquid phase as they do in the solid phase (so called "eutectic" salts)—otherwise the change of phase would be spread out over a large temperature difference and solid salt particles would separate from the mixture. Ordinary table salt (NaCl) is a eutectic salt but has too low a phase change temperature for solar thermal storage. Glauber's salt ($Na_2SO_4 + 10\ H_2O$) is an example which I have in my passive solar sunspace at home. For example, Glauber's salt stays at 32 C (94 F) and stores about 250 kJ/kg (106 Btu/lb) upon change of phase. By comparison, the same mass of water would have to cool from 60C (140 F) to 0 C (32 F) to release the same amount of heat. Salt hydrates must be encased in a sealed container to keep the water from evaporating.

Organic materials are long-chain hydrocarbons, such as paraffin wax, fatty acids, and polyglycols. Paraffin wax has a latent heat of around 200 kJ/kg (85 Btu/lb) and changes phase at 48 C (117 F). The longer the hydrocarbon chain, the higher the melting point. Thus in order to have a single phase change temperature, the media would consist of only one molecular weight, which does not occur naturally and is costly to manufacture. Organic materials must also be encapsulated in a sealed container to avoid oxidation. Despite the thermodynamic advantages, phase-change materials are not common in practice due to cost and limited service life compared with sensible storage in a water tank. Companies such as PCM Products Inc. supply stabilized phase change compounds in almost any range of phase change temperatures (PCM Products Inc. 2011)

Heat can also be stored by causing an exothermic chemical reaction, or a chemical process that absorbs heat, and then releases it again when the chemical reaction is reversed. For example, the latent heat of water is released when a desiccant absorbs moisture, and then solar heat could be used to regenerate the desiccant. If the reactants are stored in separate tanks, the energy could be stored almost indefinitely, which offers great promise for storing solar heat from summer, when it is a maximum, to winter, when it is needed most.

Most systems store energy in a heated fluid, but systems that circulate air can also store heat in a bin of rounded rocks through which the air is circulated. Steel tanks with an internal coating of glass are very common in conventional hot water systems and are also used in solar water heating systems, although some claim the large temperature fluctuations required to store more solar heat cause cracks in the glass liner. So-called "stone-lined" or cement-lined tanks have a thick inner coating that traps water depleted of oxygen and neutralized of acidity near the tank wall, extending the life of the tank. These tanks are often pressurized at the main's water pressure. Epoxy is also used to line tanks to forestall corrosion.

Fiber-reinforced plastic tanks have also been used with controls to limit the maximum temperature. For larger sizes, it is too difficult to deliver, install, and replace prefabricated tanks and is preferable to make tanks of wood, steel, masonry, or concrete with a liner. The liners are hypalon or butyl suitable for such applications (tolerance of high temperature and long service life). Kits are available with thin galvanized steel walls, urethane foam insulation, steel channel reinforcement girts, and a water-proof liner. Such site-built tanks cannot be pressurized, so they are filled with water at atmospheric pressure, and the pressurized potable water is retained in a load-side heat exchanger or coil submerged in the tank (potable water is not circulated through the tank). Unpressurized tanks with liners have piping that enters and exits through the top, because penetrations through the liner are difficult to seal. Underground concrete cisterns have also been used for thermal storage, and should be well insulated during installation with a rigid insulating material that is resistant to the ground pressure and moisture. In general, concrete tanks are not recommended because settling causes the concrete to crack, but reinforced precast tanks of the type used in septic tanks (except made without the wall penetrations) are very strong and might be suitable.

Due to the heavy weight, storage tanks are often located on the ground or in the basement of the building. In heating-dominated climates the heat loss off the storage tank helps heat the building, but in hot climates it would add to the air conditioning load. One solution is to locate the storage tank in an auxiliary room which can be vented in summer. The storage tank is often the first component of the solar system to be installed, and the other equipment positioned around it. Tanks have lives in excess of 10 years, but they do eventually require replacement, so means of getting the tank out of the building and the new tank into the building should be considered in the placement.

Prefabricated tanks will be already insulated with a protective cover of steel sheet or plastic to protect the insulation. Site-built tanks should be insulated to around R-30 ft^2Fhr/btu. Insulating the bottom of tanks present a challenge because the heavy weight of the tank would often be on the floor. But many tanks sit on struts and may be insulated to around R-20, or an insulated floor (joists and subfloor) may be built to support the tank. It is also possible to place a flat bottomed tank on about 4 inches of rigid foam insulation that is strong enough to support the distributed weight of the tank. The tank and piping connections should be checked for leaks before insulation is applied. Heat loss by transmission through the insulation is given by

$$q_{\text{tank loss}} = UA_{\text{tank}}(T_s - T_{\text{room}}) \tag{4-41}$$

Where UA_{tank} is the overall loss coefficient of the storage tank. Since the resistance of the insulation is much higher than that of convection off the surface, the loss coefficient is often approximated as $UA_{\text{tank}} = \frac{k_{\text{insul}}}{t_{\text{insul}}} A_{\text{tank}}$ where K_{insul} is the thermal conductivity and t_{insul} is the thickness of the insulation. A_{tank} is the surface area of the tank. T_s is the average temperature of

TABLE 4-11. TABLE R-VALUES OF MATERIALS USED TO INSULATE THERMAL STORAGE TANKS (PER 2.54 CM, 1 INCH, THICKNESS)

Material	R-value (m^2C/W per in)	R-value ($hrft^2F/Btu$ per in)
Fiberglass	0.76	4.3
Polyurethane	1.2	6.8
Polystyrene	0.88	5.4
Polyisocyanurate	0.97	5.5

the water in the tank and T_{room} is the temperature of the room that the tank is located in, or ambient temperature if the tank is outdoors. Usually the tank wall itself has a high conductivity and provides a negligible resistance to heat loss. The R-value is the resistance to heat loss equal to 1/U. The R-values of several common types of insulation are listed in Table 4-11 (RSMeans 2011a).

A volume of water expands as it is heated, and pressurized tanks require an expansion tank in the system to avoid rupture of the tank as the water expands. Unpressurized tanks are open to the atmosphere through a vent to avoid excessive pressure due to water expansion or high vapor pressure. This vent is a source of heat loss as vapor escapes through the vent and also leads to a need to add make-up water to the tank to compensate for the vapor loss. The vent pipe is made of copper, and a coil put into the vent pipe allows vapor to condense in the coil and drip back into the storage tank.

A sacrificial anode is installed in steel tanks to avoid corrosion of the tank walls. Access should be provided for installation of a new anode rod when the old one is spent.

There should be a drain for draining or flushing the tank. Prefabricated tanks have a boiler drain at the bottom. Site-built tanks, with the piping coming in only through the top, do not have a drain and must be pumped out.

Dissimilar metals in contact with each other cause galvanic corrosion, so the connection of copper pipe to steel tanks should be made with dielectric unions with Teflon or nylon sleeves that keep the two different metals from contacting each other directly.

Piping

The two types of pipe used in solar water heating systems are copper and plastic. Several types of plastic are used in low-temperature swimming pool systems, but the only type of plastic pipe successfully used in midtemperature solar water heating systems has been cross-linked polyethylene (PEX). Plastic pipe suitable for use in water heating systems is constructed in layers that serve purposes such as oxygen barrier, physical strength, and UV protection. Because solar collectors can produce very hot fluids, copper pipes are often recommended. Any type of plastic pipe commonly used in cold water systems but that is not rated for high temperature should not feed cold water directly into hot storage tanks; the pipe near the hot tank may bulge and break. Plastic pipe may not be compatible with all heat-transfer fluids, but is generally compatible with water and propylene glycol solutions.

Pipe diameter is often selected as a size which will result in a fluid velocity of less than 1 m/s (4 ft/s). This is generally accepted as a value which results in acceptable pipe friction and erosion. For direct residential systems, an ASHRAE design guide (ASHRAE, 1988) recommends using at least 19 mm (3/4-inch) inside diameter (ID) copper pipe. For drain-back systems, diameters less than this are found not to drain water from the collector reliably. Pipe of at least this size also prevents excessive pressure drop in the lines connecting the tank and collectors.

Example Calculation of Pipe Size

Pipe size is often selected based on a resulting velocity of 1 to 2 m/s (4 to 7 ft/s) as a velocity which does not cause scouring or erosion of pipe. It is desirable to minimize the thermal capacitance of the piping system, so here we use the higher value of 2 m/s (7 ft/s) to size the pipe. Consider eight solar collectors connected in a row by directly connecting the manifolds. The total flow rate required of the row would be that of one collector multiplied by the number of collectors in the row, 8. Now consider three such rows connected in parallel, as in Figure 4-19 illustrating balancing valves. The pipe diameter downstream of the point where the flow from two rows comes together would have to accommodate the flow of both rows. And the pipe diameter downstream of where the third row joins in would have to accommodate the sum of all three. The diameter, d (m or ft), of pipe required to carry the desired volume flow rate, V (m^2/s or ft^3/s), while maintaining the desired velocity, ν (m/s or ft/s), is given by the equation

$$d = \sqrt{\frac{4V}{\nu\pi}} \tag{4-42}$$

The flow required in each section of pipe and the required pipe diameters calculated with Equation 4-42 are listed in Table 4-12.

TABLE 4-12. EXAMPLE OF PIPE-SIZING CALCULATION FOR A SOLAR WATER HEATING SYSTEM

Flow rate per collector	0.08 l/s	1.25 gpm
Flow rate per row of 8:	0.65 l/s	10.00 Gpm
Desired velocity:	2.13 m/s	7.00 ft/s
Diameter needed for each row:	1.96 Cm	0.77 Inch
Flow rate for 2 rows combined:	1.29 l/s	20.00 Gpm
Pipe diameter to serve 2 rows:	2.78 Cm	1.09 Inch
Flow rate for 3 rows combined:	1.94 l/s	30.00 Gpm
Pipe diameter to serve 3 tows:	3.40 Cm	1.34 Inch

Picking the pipe size that meets or exceeds these required diameters, we would have to install at least 1-inch pipe to each row; downstream of where rows 1 and 2 come together we would need 1 1/4-inch pipe, and downstream of where row 3 joins in we would need 1 1/2-inch pipe, NPS.

Sizing pipe based on desired velocity is thus very easy, but a more sophisticated approach is to model the complete piping system including the cost of the pipe, the cost of the pump, and the life-cycle cost of pump power. Optimizing based on life-cycle cost is recommended, but beyond the scope of this simple example.

There are three types of copper commonly available, types K, L, and M. Type L is thicker and stronger than M and results in a quality installation designed to last the life of a building. However, type M is significantly less expensive and faster to cut and solder. Water chemistry in some locations can cause corrosion to copper, which would indicate preference for a closed loop system.

Pipe insulation is also important. However, types of insulation commonly used in lower temperature applications, such as polyethylene foam insulation should not be used because it cannot withstand the extreme temperatures and exposure to sunlight. Elastomeric insulation, which has an R-value of 3.5 per inch, is preferred for exterior and interior applications. Fiberglass insulation, which has an R-value of 3 per inch, is suitable for use in the interior of buildings; outdoors it gets saturated with water. Polyisocyanurate is also used for pipe insulation. Pipe insulation should be protected by a PVC or aluminum jacket if exposed to the outdoors.

Copper tubing expands and contracts with temperature changes (about 50C, 100F in solar systems). Using expansion loops or offsets that allow ends to flex accommodates this expansion and contraction.

Definition

Pipe Definitions

- NPS: Nominal pipe size, standard sizes for pipes specified with by internal diameter in inches (NPS) and thickness (Schedule).
- IPS: Iron pipe size, copper tube has external diameter one size less in NPS than in IPS, to consider when sizing the diameter of pipe insulation.
- Schedule: a table that specifies a thickness for each diameter of pipe. For example, the wall of Schedule 40 pipe of 1 inch diameter is 0.133 inches thick, whereas Schedule 80 is 0.179 inches thick (ANSI).
- NPT: National pipe thread (NPT), specifies compatible pipe threaded fittings.
- DN: Diamètre nominal, the European standard sizes for pipes specified by internal diameter in millimeters.

It is always useful to arrange piping to drain itself; slope can be critical in systems that rely on drainage for freeze protection.

Valves

Ball valves, gate valves, and boiler drains are the three types of valves found in solar water heating systems. Ball valves are the best valves for when a positive shut-off is required, such as required to isolate the system for maintenance. Gate valves are a less expensive alternative to interrupt the flow, but are more likely to leak past the valve and leak to the exterior of the system through the valve stem packing. Boiler drains would be found at the bottom of storage tanks and in flush-and-fill piping arrangements.

A flush-and-fill arrangement is two boiler drains separated by a check valve or a gate valve which allows the system to be flushed with fluid from and back into a single container at one location.

Bypass valves and piping allow the cold incoming water flow to be routed directly to the conventional water heater when the solar system is shut down for maintenance.

Balancing Valves

Balancing valves are similar to ball valves except that they include read-out ports upstream and downstream of the valve ball. These ports allow the pressure drop (and thus the flow) to be balanced across all the balancing valves in parallel. Balancing valves also have a stop feature which allows the valve to be closed (to maintain that section of the array) and then reopened to its previously calibrated position.

Pressure and Temperature Relief Valves

Pressure and temperature (P/T) relief valves are very important for safety. They limit the pressure of a closed system to well below that which would cause damage or injury. Pipes can contain a lot of internal pressure, but tanks with flat tops or any large flat surface can contain very little. Pressure control should limit system pressure to the lowest pressure rating among all the components. P/T relief valves should be thought of a safety devices and not be as control devices—other means must be provided to limit system pressure and the P/T valve protects against failure of that mechanism. Fluid expands as it is heated and for an incompressible fluid, like water, this increase in volume would rupture any container. Thus any component into which heat can be added must not be valved off to limit its volume, and must be fitted with a P/T relief valve in case it accidentally gets valved off. P/T valves are specified on the storage tanks, and the collector loop. The conventional water heater would also have a P/T relief valve.

Regarding the P/T valves on the collector loop, one strategy is to maintain a pressure high enough to exceed the vapor pressure of the heat-transfer fluid at the highest expected (stagnation) temperature. This is because heat-transfer fluid degrades when boiling and maintaining pressure is one means of preventing boiling. I feel, however, that it is better to employ a schematic which does not expose the fluid to high stagnation temperatures, but rather drains the fluid out of the collector when excessive temperature occurs (drain-back schematic).

Expansion Tanks

Expansion tanks can serve one, or both, of two purposes depending on the intent of the design: the first purpose is to accommodate the thermal expansion of the heat-transfer fluid; and the second purpose is to provide a volume for fluid from the collector to flow into in a drain-back or in a "steam-back" design. Since thermal expansion of the fluid will be a daily occurrence in the collector loop, an expansion tank provides a residual volume for the heated fluid to expand into. When the loop cools down again, the fluid comes back into the piping from the expansion tank. In a steam-back design, high vapor pressure of heat-transfer fluid in an overheating collector pushes the liquid volume out of the collector and into the expansion tank, leaving only vapor in the collector. The required compressed air volume inside the expansion tank is calculated by dividing the mass of fluid in the system by its density at both minimum and maximum temperature and subtracting the difference. For example, a solution of 50 percent propylene glycol and water in a solar water heating system would expand by about 15 percent volume from the expected minimum to maximum temperatures. Expansion tank volume is often 18 percent to 22 percent of total system volume. The expansion tank is not open to the atmosphere but rather maintains the same pressure as the system. Small tanks are manufactured with a rubber bladder and an air valve to pressurize the air-side of the bladder. The bladder keeps air from dissolving in the liquid. In larger systems the tank may not have a bladder but rather liquid comes in and out of the tank only through a hole in the bottom of the tank, so air is retained in the tank.

Example Calculation of Size and Location of Expansion Tank

Consider a system consisting of 24 solar collectors. According to the manufacturer's literature, each solar collector contains a fluid volume of 3 l (0.8 gal), for a total collector volume of 72.6 l (19.2 gal). Three rows of collectors are plumbed in reverse return with 46 m (150 ft) of 1 inch diameter pipe. The pipe accepting the return from the first and second rows is 15 m (50 ft) of 1 1/4 inch pipe, and the rest of the system is connected with 30 m (100 ft) 1 1/2-inch diameter pipe. The volume of a pipe of diameter *d* and length l is given by

$$V_{\text{pipe}} = \pi d^2 L/4$$

The volume contained for each of the lengths of pipe in the example are listed in Table 4-13, resulting in a total volume of 0.07 m3 (18.49 gal) for the piping system.

TABLE 4-13. EXAMPLE CALCULATION OF VOLUME ASSOCIATED WITH LENGTHS OF COMMON PIPE DIAMETERS

Diameter	Length	Pipe volume
1 inch (0.0254 m)	150 ft (46m)	0.02 m^3 (6.12 gal)
1.25 inch (0.032 m)	50 ft (15m)	0.01 m^3 (3.19 gal)
1.5 inch (0.0381 m)	100 ft (30m)	0.03 m^3 (9.18 gal)
	Total	0.07 m^3 (18.49 gal)

The total system volume is thus 0.14 m^3 (38 gal) for both the collectors and the pipe. If we want to keep the heat-transfer fluid in a liquid state and use high pressure to prevent boiling, then the expansion tank volume should be around 22 percent of the system volume, or 31.4 l (8.3 gal). Note that when using the stagnation pressure means of overheat protection that the expansion tank would have to be rated for adequate pressure, as high as 150 psi. If we wish the heat-transfer fluid to boil and the vapor to push the liquid out of the collector into the expansion tank, then we would need to accommodate the volume of the collectors as well as that of the expanding hot fluid, so the expansion tank volume would be 70 l + 30 l = 100 l (26.8 gal).

Locate the expansion tank at the inlet of the pump in order to maintain fluid available to the suction side of the pump and to make most effective use of the expansion tank volume.

Air Vents/Air Purge

Air vents are small float valve devices that allow air but not liquid to escape from the system. Air vents are used at the solar collector outlet to allow air to escape from this high point of the system, and other high points in the piping which would trap air. Air trapped in the plumbing loops interferes with fluid flow and pump operation. An "air purge" is a plumbing fixture that separates air from the fluid flow and is fitted with an air vent on top of it.

Tempering Valve

A reliable tempering valve is very important for safety. The storage tank may get very hot, and this is desirable as a means of storing more energy. The high limit of the storage tank may be set at 80C (180F), which is much too hot to send to a tap. The tempering valve mixes cold water in with the outgoing hot water, permitting elevated temperature in the storage tank without the risk of scalding building occupants.

Dielectric Unions

Corrosion is caused by dissimilar metals coming in contact with each other due to differences in galvanic potential. In order to avoid corrosion between copper piping and steel tanks or heat exchangers, di-electric unions are recommended. Dielectric unions, such as the one shown in Figure 4-26, use a layer of plastic to separate the two metals.

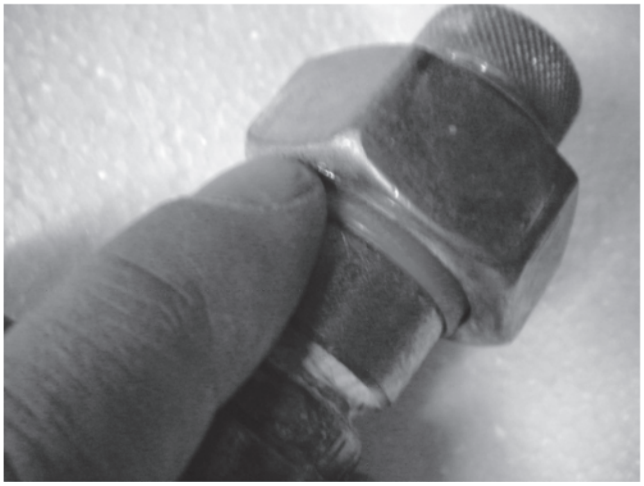

Figure 4-26. Dielectric unions use a layer of plastic to separate dissimilar metals and thus avoid corrosion due to galvanic action. (Photo by the author)

Visual Indicators

A homeowner or building occupant should be able to observe the status of the system and have confidence that it is operating properly. On each closed loop it is recommended to install:

- Pressure gauge
- Thermometer
- Flow meter

A pressure gauge with a visible readout is recommended. Thermometers with visual readouts are also desirable at multiple points on each loop, at least on hot (between collector outlet and heat exchanger inlet) and cold (between heat exchanger outlet and collector inlet) legs of the piping. For large systems, a turbine-flow meter may be justified, but for smaller systems a graduated site glass with a ball float is used. Controllers often have advanced monitoring features, some of which may displayed on the controller itself or may interface with a personal computer to display and download data.

Interview with Researcher Jay Burch

Jay Burch (Figure 4-27) is a senior physicist with 35 years of experience in experimentation, modeling, and building thermal sciences, specializing in solar thermal system monitoring and reconciliation with modeling. He manages a research program for development of low-cost solar water heating systems at the National Renewable Energy Laboratory. Jay has developed methods to calibrate models of passive solar water heating systems and buildings with short term monitoring data, and developed the corresponding software. Jay has a PhD from the University of Colorado and a BS from St. Mary's College of California in physics. He has over 80 publications in the field of building and solar thermal energy.

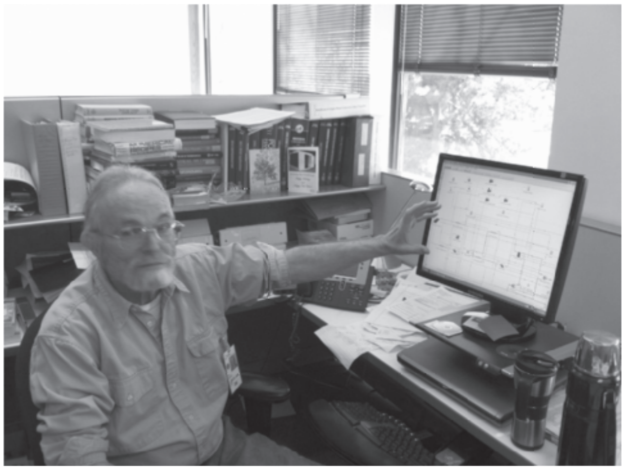

Figure 4-27. Photograph of Jay Burch modeling solar water heating systems at his computer (photo by the author)

You are conducting a lot of the research into solar water heating; what is the focus of current research?

Current research is focused on cost and reliability. Efficiency of solar thermal collectors is very high already, and there is almost no room for improvement in efficiency. The industry has done a great job squeezing out the energy, but not the costs. Depending on the application, installation firm, and a host of other factors, solar water heaters' (SWH) preincentive cost is too high to compete with low-cost natural gas. We are pursuing two paths to ultra-low-cost SWH, both predicated upon specific cold-climate thermosyphon system designs and new materials: 1) all-polymer materials/manufacturing; and 2) all-glass evacuated tubes with polymer balance-of-system. We are looking at approximately three years to initial market entry for these radically new concepts. Significant effort is going toward resistance to ultraviolet degradation and overheat protection, and we think we can increase reliability for these systems. There is no active circulation system to fail.

Are plastic systems ready for prime time? Can we go buy one?

Yes, polymer systems are available for limited applications. Unglazed plastic collectors work great for pools or any application where low temperature minimizes collector losses. Pool heating is the main solar success in the US "without substantial rebates." Unglazed collectors have also been used in low-solar-fraction water heaters, as again they are terrific at collecting energy a low temperature. These systems are on the market, and are the best choice when low solar fraction is the goal (e.g., under 30 percent, implying low-temperature operation). After several years without federal funding for low-cost SWH R&D, we are funded in late fiscal year 2012 to develop ultra-low-cost SWHs, with the first task to research a cover glazing to increase the performance of polymer collectors. Overheat protection must be addressed in glazed polymer collectors (assuming use of commodity plastics, as with all current low-cost polymer collectors).

How about plastic pipe? Is that something that designers should consider as a replacement for copper pipe in solar water heating systems?

So far, it appears only certain PEX (cross-linked polyethylene) brands have the high temperature tolerance needed, and then only in some applications. For example, CPVC has failed in a number of cases in Florida, ballooning at higher temperatures. In some jurisdictions in Oregon, PEX is required with passive systems (which bring potable water to the roof), because of its inherent freeze tolerance. In general, PEX is not approved for use with water above 180F (80C), although 210F (100C) is allowed for brief periods. PEX is allowed in SRCC OG300 only when it can be shown that high temperatures are not an issue. This has limited its use to unglazed systems and open-loop drain-back systems. If it can be used, it is less expensive, easier to install, and protects against freezing. We always postulate the use of PEX pipe with low-cost systems, but have to limit temperatures to do so.

Anything else we should know? How about solar water heating and PV integrated into the same solar collector?

PV/T is struggling in part because of the inherent conflict between the heating application wanting a high temperature and the PV wanting to be kept cool. Not-too-hot PV implies not very warm heat. This means that unless a low-temperature load like pools is present, not much high-temperature space heating/water heating load is really met with the “T,” in practice. There are now several products on the market. We feel that until concentrating PV/T matures, the low-temperature problem will hold PV/T back in the residential nonpool market.

Solar water heating is already quite common in some countries. What cost and performance targets to you think we need to meet before solar water heating really takes off in the US in the way that PV has?

The “problem” in the US is a copious supply of inexpensive natural gas (under \$10/MBtu, \$10/GJ), less than one-third the cost per Btu of our cheap electricity. This limits water heater cost savings against natural gas to about \$150/year for a 20 MBtu/year (20 GJ/year) usage. It is easy to see that you have to be under \$1,000 total installed cost (after incentives) to reach compelling economics (less than a 7-year payback, for example). Certainly there are niche markets where the cost of available heating energy is much higher, such as Hawaii and the Northeast. In the Northeastern US, the cost of solar generally needs to be less than about \$3,000, and in Hawaii less than about \$6,000. Since \$6,000 is above the post-rebate SWH cost in Hawaii, there is in fact a very robust, high-penetration market. More than 30 percent of buildings have solar in Oahu, for example.

ESTIMATING THE COST OF A SOLAR WATER HEATING SYSTEM

Initial Cost Estimate

It is necessary to estimate the cost of a solar water heating system in order to evaluate the economic feasibility of it. But we can’t do a detailed cost estimate before we do a design. Therefore, we rely on heuristic information, experience from previous projects, to provide a fairly accurate expectation of cost early in the process of developing a project. Subsequently, as a design is prepared, a detailed cost estimate may be itemized. The installed cost of the solar water heating system including all costs to provide a complete operational system, including overhead, profit, design, and any other costs related to the project is given the symbol C_{initial} in the simple economic calculations to follow.

HEURISTIC COST INFORMATION

Good sources of heuristic information regarding the cost of solar energy systems include statistics reported by government agencies and reported by programs responsible for administering incentives. The US Department of Energy reports the costs of manufacturing different types of solar water heating collectors in Table 4-14. Factory costs are reported to vary from around \$20/m^2 (\$2/ft^2) for plastic unglazed to around \$200/m^2 (\$200/ft^2) for glazed flat plate and over \$250/m^2 (\$25/ft^2) for evacuated-tube solar collectors (Wong, 2011)

These statistics from the *Solar Collector Manufacturers Activity Report*, a survey of manufacturers conducted by US Department of Energy, are total revenue divided by total factory output, so they represent what may be considered a wholesale price for just the solar collector. Retail price may be double this, and the cost of a complete and installed solar energy system divided by the collector area may be double this again, resulting in total system costs that are on the order of \$750 to \$2,500 per square meter (\$75 to \$250 per ft^2).

Costs vary depending on the type of the system, the geographic location, and the size of the system.

- Unglazed plastic swimming pool heating systems are the least expensive type, and evacuated-tube solar collectors appear to be the most expensive type of collector.
- Indirect systems with a heat exchanger and secondary heat-transfer fluid are more expensive than direct systems.
- Location affects cost: an area with an active and competitive solar industry will have lower cost than an area to which a contractor would have to travel to. For example, I was once involved in a project in Chickasaw, Oklahoma, to which the

TABLE 4-14. COSTS REPORTED TO MANUFACTURE DIFFERENT TYPES OF SOLAR WATER HEATING COLLECTORS

Type	Quantity (thousand square feet)	Revenue ($000)	Average rice (US$/ft^2)	Average rice (US$/m^2)
Unglazed	10,511	$20,411	1.94	$20.87
ICS/thermosiphon	147	$4,830	32.80	$352.93
Glazed flat-plate	1,783	$34,642	19.43	$209.07
Evacuated-Tube	328	$8,481	25.88	$278.47
Parabolic dish/trough	980	$24,814	25.32	$272.44

Source: Wong 2011.

contractor had to drive to from Albuquerque, New Mexico, a distance of over 600 miles, which would have been reflected in the cost of the system. General labor and materials also vary by location, and a good source of this effect is the City Cost Adjustment Factors for electrical, mechanical, and plumbing costs in different cities published in RSMeans cost-estimating manual (RS Means 2011a) For example, Means reports that the cost of mechanical construction varies from 67 percent of the national average in Guymon, Oklahoma to 133 percent of average in New York City.

- Size matters: unit costs ($/m^2 or $/ft^2) are dramatically higher for small systems than for large ones, and unit costs level out and approach some asymptotic value for very large systems.

For purposes of planning future renewable energy projects at sites (Walker 2009) staff at NREL has collected cost information on several past projects. Data was collected from projects in which NREL staff was involved and from Internet research, including case studies and values posted by incentive programs. Data includes all types of systems across the US, but mostly in California. Sizes range from 3 m^2 (32 ft^2) for a small domestic water heater on the author's home to 5,390 m^2 (58,000 ft^2) for an industrial process heat system at a convenience food manufacturer in Modesto, California (Walker et al. 2006). Sorting of this data by spreadsheet gives us total system costs for systems employing different types of solar water heating collectors (Table 4-15). These follow the above-stated trend of unglazed collectors being the least expensive type, but there is a lot of scatter in the data and a wide range of reported costs. Parabolic concentrator types in these tables report a very low unit cost, but these are the largest systems in the set, so economies of scale explain the low cost.

The empirical data is also sorted by the type of schematic diagram employed by the system (Table 4-16). The average costs confirm what we might expect: direct systems are less expensive than indirect systems because they don't employ a heat exchanger or nonfreezing heat-transfer fluid.

By looking across this heuristic data, we can draw a very useful conclusion: that $1,600/m^2 ($150/ft^2) is a reasonable cost expectation for a solar water heating system, and representative of most of the sizes, types of collectors, and types of systems. But the most useful heuristic will be available when your company starts installing systems in your market and using your project delivery procedures. So keep track of cost information as your company designs or builds projects and use that information to plan future projects.

DETAILED COST ESTIMATE

A heuristic cost estimate is needed prior to system design. But the schematic design establishes the detail that makes it possible to do a detailed cost estimate. The detailed cost estimate itemizes each component, and the installation labor associated with each component or the project as a whole. Adders account for overhead, profit, or any other cost adders that can be considered "percent of project." Cost estimating manuals published by RS Means are an excellent reference for detailed cost estimates (RS Means 2011a and b),and the solar water heating components and assemblies appear in both the *Mechanical Cost Data* and the *Green Building Cost Data* books (RS Means 2011a and 2011b).

TABLE 4-15. HEURISTIC UNIT COSTS OF COMPLETE SOLAR WATER HEATING SYSTEM COSTS BY TYPE OF COLLECTOR EMPLOYED

Collector type	Minimum	Average	Maximum
Unglazed	$552/m^2 ($51/ft^2)	$1,372/m^2 ($127/ft^2)	$1,691/m^2 ($157/ft^2)
Glazed flat-plate	$292/m^2 ($27/ft^2)	$1,538/m^2 ($143/ft^2)	$3,439/m^2 ($320/ft^2)
Evacuated-Tube	$1,123/m^2 ($104/ft^2)	$1,921$/m^2 ($178/ft^2)	$4,567/m^2 ($424/ft^2)
Parabolic trough	$371/m^2 ($34/ft^2)	$497/m^2 ($46/ft^2)	$604/m^2 ($56/ft^2)
All types	$292/m^2 ($27/ft^2)	$1,624/m^2 ($151$/ft^2)	$4,562/m^2 ($424/ft^2)

TABLE 4-16. HEURISTIC UNIT COSTS OF COMPLETE SOLAR WATER HEATING SYSTEMS AS A FUNCTION OF TYPE OF SYSTEM SCHEMATIC DIAGRAM

System type	Minimum	Average	Maximum
Active direct	\$627/m^2 (\$58/ft^2)	\$1,306/m^2 (\$121/ft^2)	\$2,618/m^2 (\$243/ft^2)
Direct ICS	\$1,011/m^2 (\$94/ft^2)	\$2,225/m^2 (\$207/ft^2)	\$4,490/m^2 (\$417/ft^2)
Thermosyphon	\$1,135/m^2 (\$105/ft^2)	\$1,652/m^2 (\$154/ft^2)	\$2,536/m^2 (\$236/ft^2)
Active indirect	\$292/m^2 (\$27/ft^2)	\$1,699/m^2 (\$158/ft^2)	\$3,346/m^2 (\$311/ft^2)
Drain-back	\$333/m^2 (\$31/ft^2)	\$1,503/m^2 (\$140/ft^2)	\$4,567/m^2 (\$424/ft^2)
All types	\$292/m^2 (\$27/ft^2)	\$1,624/m^2 (\$151/ft^2)	\$16,366/m^2 (\$1,521/ft^2)

In order to present an example of a detailed cost estimate, we consider the 24-collector system illustrated in Figure 4-28. For each component, we estimate the hardware and the installation cost (Table 4-17. This information is obtained from cost estimating manuals (RS Means 2011a), by searching for products for sale on-line, and by contacting suppliers.

In conclusion, our detailed estimate of \$1,456/m^2 (\$135/ft^2) is within 10 percent of our simple heuristic estimate of \$1,624 (\$151/ft^2) of Table 4-15.

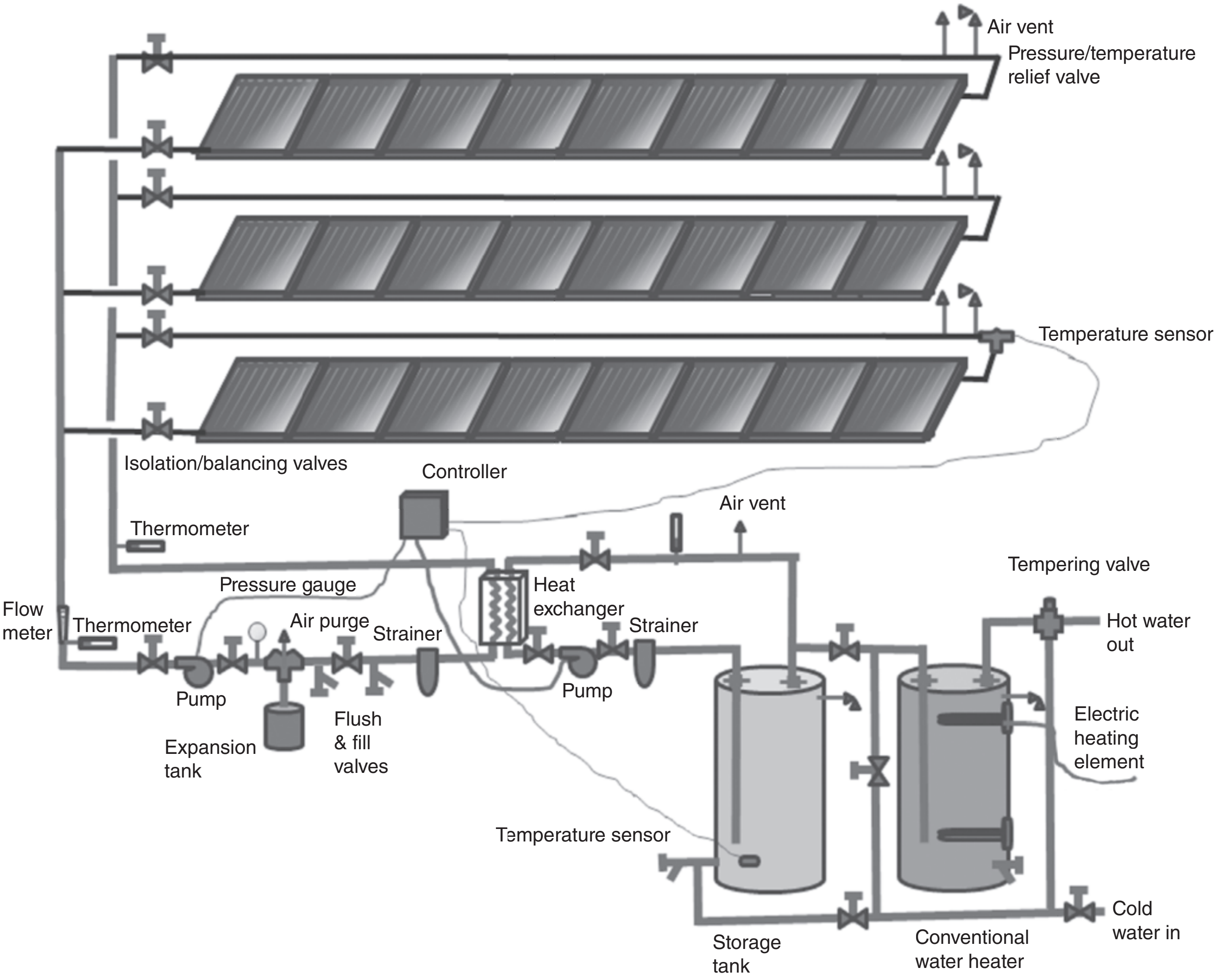

Figure 4-28. A Schematic diagram provides enough information for a detailed cost estimate. This example of a cost estimate is based on a solar water heating consisting of 24 solar collectors. (Figure by the author)

TABLE 4-17. EXAMPLE CALCULATION OF COST ESTIMATE FOR SOLAR WATER HEATING SYSTEM

System component	Quantity	Unit	Material unit cost	Installation unit cost	Total
Solar collectors; 4’ × 10’; glazed flat-plate; selective surface	24	each	$1,075	$130	$28,920
Selective surface per collector	24	Each	$200	$0	$4,800
Roof Rack	24	Each	$217	$110	$7,848
Heat-transfer fluid	40	Gallon	$15	$60	$3,000
Pump, 1 hp (1 kW)	1	Each	$425	$80	$505
Pump, 1/2 hp, (1/2 kW)	1	Each	$269	$80	$349
Strainer	1	Each	$50	$34	$84
Heat exchanger; UA = 400 kBtu/hr	1	Each	$400	$160	$560
Controller	1	Each	$165	$54	$219
Temperature sensor, 1/2″ mpt plug	2	Each	$20	$15	$70
Storage tank, 8 × 12 steel site built; Chemflex lining; 4″ fiberglass insulation	1	Each	$5,000	$1,000	$6,000
1 inch pipe, Type L copper	150	Ft	$9	$7	$2,325
1¼ inch ipe Type L copper	50	Ft	$12	$7	$993
1½ inch pipe Type L copper	150	Ft	$16	$8	$3,593
1″ pipe insulation, fiberglass	150	Ft	$1	$3	$600
1¼″ pipe insulation, fiberglass	50	Ft	$1	$3	$220
1½″ pipe insulation, fiberglass	100	Ft	$1	$3	$450
1″ pipe insulation jacket, aluminum, painted	150	Ft	$1	$4	$713
1¼″ pipe insulation jacket, aluminum, painted	50	Ft	$1	$4	$244
1½″ pipe insulation jacket, aluminum, painted	100	Ft	$1	$4	$505
1″ ball valve, stainless steel	6	Each	$91	$23	$681
1½ inch ball valve	8	Each	$180	$33	$1,704
1½ inch gate valve	2	Each	$180	$33	$426
1½ inch boiler drain valve	4		$9	$13	$90
1½ inch dielectric union	4	Each	$17	$33	$200
Expansion tank; 31 l (8.3 gal)	1	Each	$2,225	$65	$2,290
Pressure/temperature relief valve	5	Each	$555	$46	$3,005
Air purging scoop	1	Each	$895	$65	$960
Air vent	4	Each	$425	$44	$1,874
1½ inch tempering valve	1	Each	$1,225	$44	$1,269
Pressure gauge, 2″ dial display	1	Each	$22	$13	$35
Thermometer	3	Each	$31	$54	$252
Flow meter	1	Each	$565	$44	$609
Conventional water heater,	1	Each	$4,000	$1,600	$5,600
					$0
Shipping	8	Loads	$700		$5,600
					$0
Engineering, design	100	Hour	$80		$8,000
Engineering, project Management and training	200	Hour	$68		$13,631
Sub total					$108,222
Overhead and profit	20%				$21,644
Total					$129,866
				Cost per ft^2	$135
				Cost per m^2	$1,456

ESTIMATING BUILDING HOT WATER USE AND SOLAR FRACTION

Estimating hot water use is perhaps the most difficult aspect of sizing and design. For detailed analysis using computer simulation, it is desirable to know the hot water load hourly. But since the solar resource occurs daily, it is often the goal of a design to matching the energy delivery to the load on a daily basis. Thus, we wish to estimate hot water use on a daily basis (l/day, gallons/day). Different types of buildings use different amounts of hot water and at different temperatures. Even within a single type of building, hot water use varies dramatically and includes effects of climate, demographics, and occupant behavior. In retrofit applications it is possible to measure the hot water use, and even to do so with a noninvasive flow meter on a short-term basis. The electric power consumption of an electric heater or fuel consumption or run-time of a fuel-fired water heater may be measured and the hot water use inferred with an estimate of the heater's efficiency. The total power required of a water heating system is that required to heat a mass flow rate of water and that required to compensate for heat loss off the heater tank itself.

$$q_{load} = [m_{load} c_p (T_{del} - T_{mains}) + UA_{tank}(T_{del} - T_{room})] \qquad (4\text{-}43)$$

Where
m_{load} is the mass flow rate of the potable water (kg/s, lbm/hr)
c_p is the specific heat of water (around 4.2 kJ/kg/K, 1 Btu/lbm/F)
T_{del} is the desired delivery temperature (C or F). The temperature of the cold water coming into the system (the "mains water temperature," referring to the water mains bringing water to the building) T_{mains}, varies from 3.5 C (38.6 F) in Anchorage, Alaska, to 24.8 C (76.8F) in Honolulu, Hawaii, and varies from 7C (45F) in northern US to 13 C (55.0 F) locations in the southern US (FEMP 1995) UA_{tank} is the heat loss coefficient of the tank.
T_{room} is the temperature to which the tank loses heat.

If all these conditions are constant, the amount of energy required over a time period Δt (sec) is

$$Q_{load} = [M_{load} c_p (T_{del} - T_{mains}) + UA_{tank}(T_{del} - T_{room})\Delta t] \qquad (4\text{-}44)$$

The amount of fuel required is greater than the amount of heat required since some heat is lost in the efficiency of the burner. Here we divide by $\eta_{thermal}$, the thermal efficiency of the burner and exhaust-gas-to-water heat exchanger (the ratio of heat imparted to the water to fuel consumed), which does not include the losses through the insulated walls of a storage-type conventional water heater. This heat loss off the tank of the conventional water heater is not saved by the solar system.

$$Q_{fuel} = \frac{Q_{load}}{\eta_{thermal}} \qquad (4\text{-}45)$$

REFERENCE

Efficiency of Conventional Water Heater

The heat delivery of a solar water heating system is divided by the thermal efficiency of the conventional water heater, $\eta_{thermal}$, in order to estimate savings in electricity and fuel. Different measures of water heater efficiency include:

- Energy Factor (EF): this is the total energy imparted to the water divided by the fuel consumption over a standard test protocol. EF includes both inefficiency in the fuel combustion and heat transfer as well as heat loss off the outer insulation of the storage tank.
- Thermal efficiency ($\eta_{thermal}$): Thermal efficiency does not include stand-by heat loss off the storage tank, and is the ratio of heat imparted to the water divided by fuel consumption, and may be measured instantaneously.
- Loss coefficient (UA_{tank}): the loss coefficient of a storage-type water heater is the rate of heat loss divided by the temperature difference between the tank and the surroundings (W/K or Btu/hr/F)

We account for the heat loss off the tank in the estimate of total heat load, and since the conventional heater storage tank remains hot, solar heat does not eliminate tank heat loss. Rather, we divide the total heat load, both potable hot water delivery of the system and heat loss off the tank, by the thermal efficiency. Thermal efficiency for electric-heated storage systems averages 98 percent, with 100 percent being the best available. Thermal efficiency of gas-fired heaters averages 82 percent with 99 percent being the best available, and for oil-fired heaters the average is 77 percent and the best available is 84 percent (DOE BTP 2011). Energy factor (EF) is useful for comparing the advantages of a well-insulated water heater, but is not used in the calculation of savings from the solar system, rather the heat loss off the storage tank, UA_{tank}, and the thermal efficiency, $\eta_{thermal}$, are treated as two separate parameters. Often, these two parameters may be found in the manufacturer's literature. Burch and Erickson offer a means to calculate the loss coefficient, UA_{tank}, from other reported efficiencies and test conditions (Burch and Erickson 2004)

Simple Heuristic Load Estimate

The "Building America Research Benchmark Definition" by R., which provides hourly profiles for each water-using appliance in a home, is a good source of information for determining hot water usage of residential buildings (Hendron and Engebrecht, 2009). It shows a profile that peaks at about 8 a.m. and again at about 8 p.m., with a total use of 190 to 230 liters per day (50 to 60 gallons per day), depending on the temperature of the cold water that the hot water is mixed with at the tap (colder incoming water requires mixing with a higher percentage of hot water to achieve a desired temperature at the tap). Statistics of building energy use provide some insight into hot water use, and the Department of Energy Building Technologies Program's *Building Energy Data Book* is a good source of hot water use for different building types (DOE BTP 2011). Mike Deru of NREL has also analyzed hot water use in Army buildings such as barracks.[6] Table 4-18 lists the energy use intensity (energy use per square area of building floor space), and also as a fraction of the total building energy use. Deru's load data for Army buildings is at the bottom of Table 4-18 but without total building load data. For an existing building for which you know the current energy use, multiplying by the percentage of annual total energy use may be a better estimate than the absolute energy per floor area estimate. These annual totals may be divided by 365 day/year to estimate daily use.

Detailed Load Estimate of Water Consuming Fixtures

In cases where the hot water process loads are well understood, an estimate of hot water use may be derived from the details of the fixture hot water flow rate and run time. Hot water use events may be measured, or if the design is of a new building, they may be estimated from manufacturer's literature regarding appliances (clothes washer, dishwasher). EPA Energy Star criteria may be referred to for the hot water use of household and smaller commercial products.

Measuring Hot Water Use

Despite our best attempts to predict hot water use through simple heuristic or detailed estimates, in the few instances that we get to compare these estimates to actual water use, they differ considerably. Thus, it is recommended that the actual building load be measured rather than estimated. However, be observant as to whether the building is currently used as intended. (Take measurements on ordinary working days. Is the tempo of the operations typical?) Approaches to measuring on-site load include:

> Utility gas meter. Analysis of the readings of the utility revenue meter already in place may provide an estimate of energy used for water heating. Natural gas is typically used for space heating and water heating. In warm months, the space heating load may be zero, leaving a measurement of the hot water energy use. In some cases, submetering may already be in place in order to monitor or control processes in a facility.

TABLE 4-18. ESTIMATES OF HOT WATER USE AS A FRACTION OF TOTAL ENERGY USE FOR DIFFERENT TYPES OF BUILDINGS

Type of Building	Hot Water Use (kWh/m^2/year)	Hot Water Use (kBtu/ft^2/year)	Percent of Annual Total Energy Use for hot water
Education	18.3	5.8	6.98%
Food sales	9.1	2.9	1.45%
Food service	127.4	40.4	15.64%
Health care	95.2	30.2	16.09%
Inpatient	152.6	48.4	19.42%
Outpatient	7.9	2.5	2.64%
Lodging	99.0	31.4	31.40%
Mercantile	16.1	5.1	5.59%
Service	3.2	1.0	1.30%
Retail	3.5	1.1	1.49%
Shopping mall	24.3	7.7	7.53%
Office	6.3	2.0	2.15%
Assembly	3.2	1.0	1.06%
Public safety	44.2	14.0	12.09%
Worship	2.5	0.8	1.84%
Storage	1.9	0.6	1.33%
Army administration	14.9	4.7	
Army barracks	33.2	10.5	
Army dining hall	43.1	13.7	
Child care center	7.4	2.3	
Other	6.6	2.1	
Vacant	0.3	0.1	

Source: DOE BTP 2011; information from Michael Deru, NREL, 2012.[6]

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[6] Interviewed by A. Walker. March 3, 2012, Golden, Colorado.

TIP

Efficiency First

What's the most efficient way to heat water? Don't use it in the first place! Almost any measure taken to reduce hot water use is less expensive than investing in a solar energy system to heat that amount of saved water. Certainly this includes low-cost measures such as low-flow shower heads, but often includes replacing more expensive hot water appliances such as clothes washers and dishwashers with newer, more efficient ones. In new construction, the premium paid for high-efficiency appliances is justified. Strategies to reduce the cost of water heating include:

1. Increase the awareness of the occupants not to waste hot water. For example, post instructions to wash dishes in a soapy basin rather than to let the water run as they are washed.
2. Low-flow fixtures for faucets and showers.
3. Water-conserving appliances such as horizontal-axis clothes washers.
4. A recirculation pump to keep hot water at the tap so that water doesn't run to drain waiting for water at the tap to become hot.
5. Heat recovery heat exchanger (like a copper pipe wrapped around the drain line) to exchange heat from the drain water to the supply water.

Some of these measures cost a lot of money, but they can actually be less expensive than the purchase of a solar water heating system to heat the amount of water saved. Efficiency measures are compelling because they save energy themselves, but they also save considerably on the required size of a solar water heating system for a building.

Run time meter. Very small, inexpensive run time meters are available that may be triggered by the electric signal to an electric heating element or an electrically powered gas valve. This is useful if the device is either on or off, rather than on partial power.

Btu-meter. A "Btu-meter," or energy meter, consists of a flow meter and two temperature sensors. One of the temperature sensors is placed on the cold water coming into the heating system and the other on the hot water going out to the load, thus measuring the temperature difference imparted to the water. Integrating electronics are required to multiply the flow and temperature difference in real time, since the average of the product is not equal to the product of the averages. Noninvasive flow and energy metering makes measurements quick and affordable, but the ultrasonic flow meters are expensive and require some training.

Example Calculation of Hot Water Load Estimate

Consider a small laundry building with 10 clothes washing machines. Each machine uses 102 l (27 gallons) per load of laundry according to the manufacturer's literature. The average of 4 loads per washer per day is determined by counting the amount of money collected by each coin-operated machine in a typical day. The hot water is provided by an electric storage-type water heater with a thermal efficiency of 98 percent and a heat loss coefficient of 1.4 btu/hr/F (7.9 W/C), according to the manufacturer's literature. Assume for this example that cold water comes in at 15°C (60°F) and is heated to 60°C (140°F).

Before investing in solar, we consider all possible efficiency measures. Let's recommend that the clothes washers be replaced with horizontal-axis clothes washers that use only 68 l (18 gallons) per load. Also, by circulating cold incoming water through a coil heat exchanger submerged in the basin used to keep solids from going down the drain, the T_{mains} may be increased from 15°C (60°F) to 20°C (68°F).

The daily hot water load is thus (18 gallons/load)*(40 loads/day) = 720 gallons/day (2,700 liters/day).

$$Q_{\text{load}} = \left(2{,}700\frac{\text{kg}}{\text{day}}\right)\left(\frac{4200J}{\text{kg}K}\right)(60C - 20C) + \left(7.9\frac{W}{C}\right)(60C - 20C)\left(\frac{24\text{hours}}{\text{day}}\right)\left(\frac{3600s}{\text{hr}}\right)$$

$$= 481 \text{ MJ/day} = 133 \text{ kWh/day}$$
$$= 0.48 \text{ million Btu/day}$$

The amount of fuel (in this case electricity) burned (used) to create this much heat would be determined by dividing by thermal efficiency

$$Q_{\text{fuel}} = \frac{133\frac{\text{kWh}}{\text{day}}}{0.98} = 136\frac{\text{kWh}}{\text{day}}$$

RECOMMENDED APPLICATIONS

Residential Water Heating

Residential water heating is perhaps the best application for solar water heating because water is used at several times of day, seven days a week, and 52 weeks per year. The amount of hot water used is highly variable from house to house, and it is common to design the solar water heating system to the number of bedrooms and presence of other hot water loads such as clothes washer, rather than the habits of the current occupant. Residential hot water use may be on the order of 20 gal/day/person in the US but is much less in most other countries.

Hospitals

Hospitals are also using water at any time of day and every day of the year. Hospitals use a very large amount of hot water, probably for very extensive cleaning and bathing use but also for food preparation and laundry. Adequate roof space is usually available. Hospitals use on the order of 18 gal/day/person of hot water.

Detention Facilities (Prisons)

Much like hospitals or residences, prisons make excellent use of solar hot water due to usage every day of the year. And they are often away from dense urban development, so they are more likely to have land available for locating solar collectors. Prisons may be exempt from some of the aesthetic objections to solar, but they come with security objections. Ground mounted arrays obstruct the vision of guards. A prison north of Phoenix, Arizona, put the solar array outside the fence and uses underground pipe to deliver hot water to cellblock, laundry, and food service buildings.

Hotels/Motels

In hospitality industries aesthetics are at a premium, and generally solar collectors would have to be mounted where they are not visible. The "flagship" properties of a hotel chain are often in dense urban areas without roof or land area, but there are also low-rise properties where solar would not affect the visual aesthetics on the roof. Hot water use in hotel/motels may be on the order of 15 gal/day/person.

Food Service

Food service establishments are usually good applications for solar water heating because they use a lot of hot water for cooking and cleaning and they are often open for business 7 days a week and 12 months a year. Hot water use varies from less than 1 gal/meal to over 2.4 gal/meal, depending on the types of foods, the nature of the service, and the use of dishes or disposable packaging.

Air Conditioning Reheat

Air conditioning systems dehumidify air by cooling it down past the dew point and then heating it back up again. Failure to reheat causes humidity problems in buildings. This reheat is provided very well by solar, especially since the air conditioning load is partially due to solar heat gain on the building, so the two would be coincident. This would be indicated in sunny and humid (tropical) locations.

Swimming Pool Heating

Swimming pools are equipped with very large heating equipment in order to heat make-up water and compensate for heat loss due to evaporation and heat loss to the surroundings. It is a common misconception that the huge volume of a pool or spa make good solar thermal storage—since we wish to keep the pool at a uniform temperature, it is usually not feasible to store a large amount of solar heat in the pool. It is, however, very possible to add enough solar heat to balance daily heat loss and make it affordable to extend the swimming season well past Labor Day. Since the temperature of the pool is low compared to other water heating uses, a simple, low-cost, unglazed solar collector operates at a high efficiency. A solar water heating system is easily connected using plastic pipe compatible with the pool pump/filter/heater system.

First we must recognize that the surface of the swimming pool itself is a solar collector, and with a plastic cover to retain heat, a pool may be kept as much as 10°C (20°F) warmer simply with diligent use of a pool cover.

I have been involved in several solar swimming pool projects, and the recommended area (m^2, ft^2) of the solar collectors is often about half that of the pool surface. Separate unglazed plastic solar collectors heat water as it is circulated through the filtration system and may be located on the ground outside the pool enclosure, on the roof of a pool cabana or service building, or on a new shade structure.

SIMPLE HAND CALCULATION OF SOLAR WATER HEATING SYSTEM SIZE AND ENERGY DELIVERY

The size of a solar water heating system is best determined by life-cycle cost optimization, considering the diminishing returns of making the collector larger. But that is a complicated analysis requiring computer simulation. Computer simulation allows detailed treatment of the utilization of solar energy if the load is not always enough to use the solar heat. Still, we find a simple hand calculation to be very useful early in design and often sufficient to see a project through to completion. Analysis of the energy delivery and economics of a solar water heating system involves:

- The mass of hot water used at the site and the timing of the hot water draws
- The temperature at which cold water is introduced into the system and the temperature at which hot water exits the heating system
- Insolation, the amount of sunshine at a location
- Type and efficiency of the system
- Size and cost of the system
- Price of conventional fuels (are the utility rates high in the site area?)
- Rebates, tax credits, and other incentives available
- Annual operation and maintenance costs.

Sizing the area (m^2, ft^2) of the solar collector

This simple hand calculation considers a sizing approach based on matching the hot water use with solar delivery on a sunny day, and the using conventional heating on short or cloudy days when the solar is not sufficient to meet the load.

The size of the solar collector area required to meet the load on the sunniest days is

$$A_c = \frac{Q_{\text{load}}}{I_{c,\max}\eta_{\text{solar}}} \tag{4-46}$$

Where A_C = collector area (m^2); Q_{load} = daily hot water energy load (kWh/day); η_{solar} = efficiency of the solar energy system averaged over the day. Insolation $I_{C,\max}$ is the maximum daily solar radiation (kWh/m^2/day) expected over the course of the year, usually in June for northern latitudes. We divide by $I_{\max}$ rather than average in the equation to determine the size so that the system is designed to meet the load on the sunniest day of the year, which eliminates excess capacity and optimizes economic performance. In the winter, or after a stretch of cloudy days, the conventional fuel supply would provide more of the hot water. A paper by Craig Christensen of the National Renewable Energy Laboratory and Greg Barker of Mountain Energy Partners, presents calculated efficiency for domestic solar water heaters in 243 locations, and reports that efficiency varies between 26.4 percent and 44.3 percent, depending on location and hot water load, with an average of 40.2 percent for all locations and load profiles (Christensen and Barker 1998). An annual system efficiency of around 40 percent is often estimated by computer simulations, but results of monitoring actual, installed systems indicate efficiency is actually less than estimated by simulation. That stands to reason: of all the things that could be different between the actual system and the model, how many do you think improve performance? I have measured efficiency of 25 percent on a group of residential systems in Hawaii, 30 percent on my system at home, and 33 percent on a prison near Phoenix Arizona (Walker and Roper 1992a; May et al. 2000; Walker, Christensen, and Yanagi 2003). Thus a recommended value for η_{solar} for use in the simple calculations to follow is 30 percent.

Sizing the Volume (m^3, Gallons) of the Thermal Storage Tank

The storage tank must be large enough to store the solar heat available during the day that is in excess of the hot water load during the day. Storage size must also include thermal storage to compensate for heat loss off the storage tank itself. For an intermittent load such as a single residence, the storage should be sufficient to accept all of the solar delivery on a sunny day. A value for $\Delta T_{\text{storage}}$ of 20C (40F) is a reasonable design criteria.

$$M_{\text{storage}} = \frac{A_C I_{C,\max,\text{day}} \eta_{\text{solar}}}{c_{p,\text{storage}} \Delta T_{\text{storage}}} \tag{4-47}$$

Where A_C = collector area (m^2) and η_{solar} = efficiency of the solar energy system averaged over the day. Insolation $I_{C,\max,\text{day}}$ is the maximum daily solar radiation (kWh/m^2/day) expected over the course of the year, usually in June or July for northern latitudes. We divide by $I_{\max}$ rather than average in the equation to make sure the storage is big enough to capture daily solar heat in the summer. For applications that have a regular (not intermittent) hot water use during the day, such as a hospital, the solar heat would be used immediately and so the storage could be reduced.

$$M_{\text{storage}} = \frac{[A_C I_{C,\max,\text{day}} \eta_{\text{solar}} - m_{\text{laod}} c_p (T_{\text{del}} - T_{\text{mains}}) * \text{sunhours}]}{c_{p,\text{storage}} \Delta T_{\text{storage}}} \tag{4-48}$$

Here sunhours is approximated by $I_{C,\max,\text{day}}$/(1 kW/m^2) and mass flow rate to the load would have to be in kg/hour.

Annual Energy Savings

Heat delivered annually by the solar system can be estimated using the following equation:

$$Q_{\text{solar,year}} = A_c I_{c,\text{ave}} \eta_{\text{solar}} \left(365 \frac{\text{days}}{\text{year}}\right) \tag{4-49}$$

And the savings in fuel or electric energy can be estimated by dividing this savings by the thermal efficiency of the conventional heating system:

$$Q_{\text{Fuel Savings}} = \frac{Q_{\text{solar}}}{\eta_{\text{thermal}}} \tag{4-50}$$

Where $Q_{\text{Fuel Savings}}$ is annual fuel or electricity energy savings (kWh/yr), $I_{C,\text{ave}}$ is annual average solar radiation (kWh/m^2/day); η_{boiler} is the thermal efficiency of the fuel-fired or electric water heater. The energy factor (EF) includes standby losses from the storage tank, which could not be saved by the solar water heating system. But the thermal efficiency accounts for combustion and exhaust heat exchanger losses, which would be saved by the solar system.

Thus the two pieces of information that we need regarding the solar resource at a site are the maximum daily solar insolation for sizing the collector and then the average daily solar insolation for estimating the energy savings.

Annual Cost Savings of Solar Water Heating System

Annual energy cost savings may be estimated by multiplying annual energy savings by unit cost of energy, and by accounting for the additional pump power required to circulate the heat-transfer fluid. The annual cost of operating and maintaining the solar water heating system $C_{\text{O\&M}}$, is subtracted to estimate annual cost savings

$$C_{\text{saving}} = Q_{\text{Fuel Savings}} c_{\text{fuel}} - Q_{\text{pump}} C_{\text{electricity}} - C_{O\&M} \tag{4-51}$$

TABLE 4-19. MAXIMUM DAILY AND AVERAGE DAILY SOLAR RADIATION: GLOBAL INSOLATION ON TILT = HORIZONTAL SURFACE FOR FLAT PLATE COLLECTORS AND DIRECT BEAM INSOLATION ON NORTH-SOUTH AXIS TRACKING AZIMUTH OF THE SUN FOR FOCUSING COLLECTORS FOR CITIES IN THE US, IN ORDER OF NAME OF STATE.

		Global Tilt = Horizontal Flat Plate Collectors (kWh/m²/day)		Direct Beam N-S Axis Focusing Collectors (kWh/m²/day				Global Tilt = Horizontal Flat Plate Collectors (kWh/m²/day)		Direct Beam N-S Axis Focusing Collectors (kWh/m²/day				Global Tilt = Horizontal Flat Plate Collectors (kWh/m²/day)		Direct Beam N-S Axis Focusing Collectors (kWh/m²/day	
State	**City**	$I_{C,max}$	$I_{C,ave}$	$I_{C,max}$	$I_{C,ave}$	**State**	**City**	$I_{C,max}$	$I_{C,ave}$	$I_{C,max}$	$I_{C,ave}$	**State**	**City**	$I_{C,max}$	$I_{C,ave}$	$I_{C,max}$	$I_{C,ave}$
Alabama	Huntsville	5.7	4.8	4.9	3.5	Florida	Tampa	6.3	5.3	5.7	4.0	New York	Buffalo	5.5	4.1	4.9	2.7
Alaska	Anchorage	4.6	3	3.5	1.8		Orlando	5.8	4.8				New York	5.6	4.6	4.1	2.9
	Juneau	4.5	1.1	6.4	0.6		Key West	6.4	5.5	6.0	4.4	North Carolina	Charlotte	5.7	5	4.8	3.7
Arizona	Chandler	6.9	5.4				Fort Lauderdale	5.9	5				Raleigh	5.7	4.7	4.6	3.5
	Flagstaff	6.7	4.9	8.6	5.6	Georgia	Atlanta	5.8	5.1	4.9	3.7		Greensboro	5.7	5.0	4.7	3.6
	Mesa	6.8	6.1			Hawaii	Hilo Honolulu	5.2 6.2	4.8 5.7	4 6	3.3 4.8	North Dakota	Fargo	6	4.6	6	3.4
	Phoenix	7.5	6.5	8.9	6	Idaho	Boise	7	5.1	8.7	4.5	Ohio	Columbus	5.4	4.2	7.6	4.9
	Scottsdale	7	6			Illinois	Aurora	5.3	3.8			Oklahoma	Oklahoma City	6.3	5.4	6.5	4.4
	Tucson	7.3	6.5	8.9	6.2		Joliet	5.5	4.1			Oregon	Portland	5.8	3.9	5.4	2.6
California	Bakersfield	7.3	5.7	8.7	5.2		Chicago	5.7	4.4	4.8	2.9		Salem	6.1	4.1	6.1	2.9
	Chula Vista	6.6	5.5			Indiana	Fort Wayne	5.6	4.3	4.7	2.9	Pennsylvania	Philadelphia	5.5	4.6	4.6	3.1
	Fresno	7.3	5.7	8.8	5.1	Kansas	Overland Park	5.8	4.5			Rhode Island	Providence	5.5	4.5	4.4	3
	Inyokern	7.2	6.3				Wichita	6.3	5.2	6.3	4.2	South Carolina	Columbia	5.9	5.1	5	3.7
	Lancaster	7.1	6.0			Kentucky	Lexington-Fayette	5.6	4.5	4.7	3.1	South Dakota	Sioux Falls	6.1	4.8	6.1	3.6
	Long Beach	6.3	5.6	6.6	4.4	Louisiana	Shreveport	6	5.1	8.2	6	Tennessee	Memphis	6	5	5.4	3.8
	Modes	7	5.1				New Orleans	5.7	5	4.8	3.6	Texas	Amarillo	6.4	5.8	6.8	5.1
	Ontario	6.2	5			Maine	Bangor	5.0	3.7				Arlington	6.2	4.8		
	Oxnard	6.1	5.3			Maryland	Baltimore	5.6	4.6	4.8	3.3		Brownsville	5.9	5	5.2	3.6
	Palmdale	7.1	6.1			Massachusetts	Boston	5.6	4.6	4.6	3.1		Dallas/Fort Worth	6.4	5.4	6.2	4.3

	Riverside	6.3	5.1			Michigan	Houghton	5.6	4.1	5.3	2.9		El Paso	7.3	6.5	8.2	6
	Sacramento	7.2	5.5	8.8	4.9		Detroit	5.6	4.2	4.8	2.8		Houston	5.5	4.8	4.5	3.4
	San Diego	6.5	5.7	6.2	4.6	Minnesota	Duluth	5.6	4.4	5.2	3		Laredo	6.2	5		
	San Francisco	6.8	5.4	7.1	4.4	Mississippi	Natchez	5.4	4.6				Lubbock	6.3	5.8	6.7	5.1
	Santa Rosa	6.9	5.3			Montana	Billings	6.5	5	7.4	4		San Antonio	6.3	5.4	5.7	4.1
	Stockton	7.1	5.1				Kalispell	6.2	4.1	6.9	3.2	Utah	Salt Lake City	6.7	5.3	7.6	4.5
	Truckee	7	5.1			Missouri	St. Louis	5.9	4.8	5.3	3.5		Provo	6.9	5		
Colorado	Eagle	6.4	5.5	7.3	4.7	Nebraska	Omaha	6	4.9	5.5	3.6	Vermont	Burlington	5.6	4.3	4.9	2.8
	Alamosa	6.8	6.3	6.8	4.8		Lincoln	5.7	4.3			Virginia	Richmond	5.6	4.8	4.7	3.4
	Denver	6.1	5.5	6.6	4.6	Nevada	Las Vegas	7.4	6.5	9.1	6.2		Chesapeake	5.4	4.5		
	Fort Collins	6.4	5.1				Reno	7.1	5.8	8.8	5.4		Norfolk	5.6	4.8	4.7	3.4
	La Junta	6.7	5.2			New Hampshire	Concord	5.6	4.6	4.9	3.2	Washington	Yakima	6.7	4.8	7.8	4.0
Connecticut	Hartford	5.4	4.4	4.1	2.8	New Jersey	Newwark	5.4	4.5	4.2	3	Washington	Seattle	5.7	3.7	5.2	2.5
Delaware	Wilmington	5.6	4.6	4.7	3.2	New Mexico	Albuquerque	7.2	6.4	8.4	5.9	West Virginia	Huntington	5.4	4.3	4.3	2.9
Florida	Jacksonville	6	5	5.3	3.7		Las Cruces	7.1	6.5	7.1	5.4	Wisconsin	Madison	5.8	4.5	4.8	3.0
	Miami	6.1	5.2	4.9	3.6	New York	Albany	5.5	4.3	4.5	2.8	Wyoming	Cheyenne	6.1	5.3	6.5	4.4
													Dubois	6.2	4.8		

Source: NASA LARC 2012.

TABLE 4-20. MAXIMUM AND AVERAGE DAILY SOLAR INSOLATION ON TILT = LATITUDE FOR CITIES IN VARIOUS COUNTRIES, BY COUNTRY

Country	City	I_{max} (kWh/ m^2/day	$I_{C,ave}$ (kWh/ m^2/day)	Country	City	I_{max} (kWh/ m^2/day	$I_{C,ave}$ (kWh/ m^2/day)	Country	City	I_{max} (kWh/ m^2/day	$I_{C,ave}$ (kWh/ m^2/day)
Afghanistan	Kabul	7	5.9	Congo	Kinshasa	4.9	4.2	Korea, S.	Seoul	5.5	4.7
Albania	Tirana	6.9	5.1		Lubumbashi	7	5.9	Korea, S.	Suwon	5.5	4.7
Algeria	Algiers	6.3	4.8	Cook Islands	Pukapuka	5.9	5.6	Kuwait	Kuwait City	6.9	5.8
Angola	Luanda	5.7	4.9	Costa Rica	San José	6.3	5.1	Kyrgyzstan	Osh	6.0	5.2
Argentina	Buenos Aires	6.3	5	Côte d'Ivoire	Abidjan	5.4	4.7	Latvia	Riga	4.6	2.7
	Mendoza	6.7	5.5	Cuba	Havana	6.3	5.5	Lebanon	Beirut	6.2	5.0
	Ushuaia	4.7	3.1	Czech Republic	Prague	4.5	3.2	Macedonia	Skopje	6.0	4.4
Australia	Adelaide	6.2	5.1	Denmark	Copenhagen	4.8	3.1	Madagascar	Antananarivo	5.6	4.8
	Alice Springs	6.9	6.5	Egypt	Cairo	6.7	5.7	Malasia	Kuala Lumpur	5.0	4.5
	Canberra	6.6	5.2	England	Leeds	4.1	2.9	Mali	Bamako	6.5	5.8
Austria	Vienna	4.8	3.6		London	4.1	2.8	Mexico	Chihuahua	6.9	6.3
Azerbaijan	Baku	5.5	4.2	Ethiopia	Addis Ababa	5.9	5.1		Merida	6.2	5.5
Bahamas	Nassau	6.6	5.8	Finland	Helsinki	5.1	3.1		Mexico City	6.3	5.3
Bangladesh	Chittagong	5.8	4.9	France	Marseille	6.4	4.9		Monterey	6.2	5.5
	Dhaka	6	5		Paris	5.0	3.2	Mongolia	Ulan Bator	6.0	4.7
Belarus	Minsk	4.6	2.9		Lyon	5.7	3.7	Morocco	Casablanca	5.8	4.9
Belgium	Antwerp	4.6	3.2	Georgia	Tbilisi	5.5	4.0	Mozambique	Maputo	6.2	5.6
Belize	San Ignacio	6.1	5.1	Germany	Frankfurt	4.3	3.1	Myanmar	Mandalay	6.5	5.4
Bhutan	Thimpu	5.6	5.2		Hamburg	4.5	2.9		Yangon	6.5	4.9
Bolivia	Santa Cruz	5.2	4.8		Munich	4.7	3.6	Nepal	Kathmandu	6.9	5.8
Bosnia	Sarajevo	5.3	3.8	Iceland	Reykyavik	4.1	2.6	Netherlands	Amsterdam	4.9	3.2
Brazil	Rio de Janeiro	5.7	4.9	India	Ahmadabad Gujarat	7.0	5.9	New Zealand	Aukland	6.0	4.5
	Brasília	6.2	5.5		Bangalore	6.1	5.4	Nicaragua	Managua	6.8	5.9
Canada	Edmonton	5.9	4.8		Bhopal	6.5	5.4	Nigeria	Lagos	5.6	4.8
	Montreal	4.8	3.9		Calcutta	6.1	5.1	Norway	Oslo	4.8	3.3
	Saskatoon	5.9	5.2		Chandigarh	6.6	5.8	Pakistan	Faisalabad	6.2	5.5
	Toronto	5.5	3.9		Delhi	6.8	5.7		Gujranwala	6.7	5.9
	Vancouver	5.6	3.6		Dhera Dun Uttaranchal	6.8	5.9		Hyderabad	6.3	5.5
	Winnipeg	5.7	4.6		Gauhati Assam	6.2	5.2		Karachi	6.1	5.7
	Yellowknife	5.5	3.2		Goa	6.8	5.7		Lahore	5.8	5.1

Chile	Punta Arenas	5.1	3.4		Hyderabad	6.6	5.2		Multan	6.0	5.5
	Santiago	5.9	4.0		Itanagar Arunchal	4.9	4.3		Peshawar	6.5	5.8
China	Baotou Neimongol	6.3	5.5		Kargil Kashmir	6.1	5.3		Quetta	6.8	6.0
	Beihai Guangxi	4.6	4.2		Leh Ladakh	6.5	5.6	Paraguay	Asunción	5.8	5.1
	Beijing	5.0	4.3		Lucknow Uttar	6.3	5.3	Peru	Lima	7.1	5.4
	Changsha Hunan	4.8	3.2		Ludhiana Punjab	6.6	5.8	Philippines	Davao	5.6	5.0
	Chengdu Sichuan	3.4	2.5		Madras	6.8	5.5	Poland	Warsaw	4.7	2.9
	Chungking	3.6	2.4		Manali Himachal	5.6	5.0	Russia	Grozny Chechnya	5.3	4.2
	Fuzhou Fujian	4.9	3.4		Mumbai	6.6	5.4		Moscow	4.9	3.1
	Guangdong Tianjin	5.9	5.1		Patna Bihar	6.9	5.6	Saudi Arabia	Jidda	6.8	6.2
	Ganzhou Jiagxi	4.9	3.7		Pune	6.9	5.7	Scotland	Edinburgh	4.2	2.9
	Guiyang, Guizhou	3.9	2.7		Shrinagar Kashmir	6.4	4.9	Senegal	Dakar	6.8	5.8
	Haikou Hainan	5.1	4.5		Trivandrum	6.4	5.5	Somalia	Mogadishu	7.2	6.7
	Harbin Heilongjiang	5.0	4.3	Indonesia	Jakarta	4.4	4	South Africa	Cape Town	6.9	5.6
	Hefei Anhui	4.3	3.7		Palembang	5.0	4.7		Pretoria	6.4	5.9
	Hong Kong	4.9	4.1	Iran	Shiraz	6.7	5.9	Spain	Barcelona	6.2	5.0
	Jilin Jilin	5.8	5		Tabriz	6.8	5.1		Seville	6.6	5.4
	Jinzhou Liaoning	5.7	4.7		Tehran	6.8	5.4	Sweden	Linkoping	4.8	3.4
	Kunming Yunan	5.5	4.4	Iraq	Baghdad	6.4	5.5	Switzerland	Geneva	5.3	3.6
	Lanzhou Gansu	5.0	4.2		Mosul	5.6	4.4	Syria	Aleppo	6.8	5.2
	Lhasa Tibet	6.9	6.2	Ireland	Dublin	4.2	2.8	Taiwan	Taipei	4.6	3.7
	Tsingtao Shandong	3.7	3.4	Israel	Haifa	6.8	5.5	Tajikistan	Dushanbe	7.1	5.1
	Shanghai	4.4	3.6	Italy	Milan	5.6	4.2	Tanzania	Dar es Salaam	5.3	4.8
	Shenzhen Guangdong	4.6	4.0		Palermo	7.1	5.4	Thailand	Bankok	5.7	4.9
	Shijiazhuang Hebei	5.9	5		Venice	5.3	3.6	Tunisia	Sidi Bou Said	6.6	5.0
	Suzhou Jiangsu	4.6	4.1	Japan	Akita	4.6	3.5	Turkey	Antalya	6.4	4.9
	Urumqi Xinjiang	5.7	4.4		Nagasaki	5.6	4.4		Bursa	6.1	4.3
	Wuhan Hubei	4.4	3.3		Sapporo	4.6	3.8		Istanbul	6.6	4.5
	Xian Shaanxi	4.4	3.8		Tokyo	3.7	3.2	Uganda	Kampala	6.5	5.5
	Xining Qinghai	5.8	4.7		Yamagata	4.6	3.6	Ukraine	Odessa	5.5	3.7
	Yanchi Ningxia	5.9	5.3	Kazakhstan	Karaganda	5.7	4.5	Venezuela	Caracas	5.0	4.5
	Zhengzhou Henan	5.3	4.2	Kenya	Nairobi	6.6	5.3	Virgin Islands	Charlotte Amalie	7.0	6.3
Columbia	Bogota	5.2	4.3	Korea, N.	Pyongyang	5.0	4.2	Yemen	Sana'a	5.3	4.6

Sources: NASA LARC 2012; Minister of Natural Resources Canada 2012.

Where $C_{savings}$ is annual cost savings (\$/year); C_{fuel} is the unit cost of the electricity or fuel used to heat water (\$/kWh) and $C_{electricity}$ is the unit cost of electricity consumed by the pump (\$/kWh), or fan in an air system.

Life-Cycle Cost Analysis of Solar Water Heating System

A simple economic model is often adequate to evaluate life cycle cost of a solar water heating system. The life cycle cost, *LCC*, is the initial cost of purchasing and constructing the solar water heating system and the annual savings in energy and operations costs. The net present value of the life cycle savings, *LCS*, of a project may then be approximated by

$$LCS = (C_{savings})PWF(d,\, N) - C_{initial} \tag{4-52}$$

Where the present worth factor, PWF(d,N), is the factor to discount, at the rate of d percent per year, a stream of N annual cash flows down to their present value. For example, the PWF for $N = 25$ years of cash flows at $d = 3$ percent discount rate is 17.4 years. The PWF has units of years, but it reflects that the value of \$1/year for 25 years is worth only \$17.4 today.

Another useful metric is the savings to investment ratio, or SIR, which is the ratio of life cycle savings to the investment.

$$SIR = \frac{C_{savings}PWF(d,N)}{C_{intial}} \tag{4-53}$$

An SIR of greater than one (SIR > 1) indicates that a project is cost-effective. The size of the solar water heating collector, initial cost, annual energy delivery, annual cost savings, and payback period may be estimated by this simple hand calculation, but subsequently more detailed analysis using computer tools must be used to refine the estimate of economic savings.

Example Calculation of of Size, Cost, and Heat Delivery of Solar Water Heating System

In this example, we consider solar heating of water for a small laundry building with 12 clothes washing machines. The energy consumption of the electric storage-type water heater is 168 kWh/day (0.56 million Btu/day) similar to that detailed in the preceding load calculation example.

The building is located in Denver, Colorado, and hot water is used 7 days a week. Referring to the table of solar resource data above, we find Denver Colorado, and the value of I_{max} is 6.1 and the value of $I_{C,ave}$ is 5.5 kWh/m^2/day (NASA LARC 2012). For the economic analysis, the detailed cost estimate is \$129,866, or \$1,456/m^2 (\$135/ft^2) for the complete and installed solar water heating system. The price of electricity for both heating water and running the pump is \$0.18/kWh. Assuming a 3 percent discount rate and a 25-year analysis period, the present-worth factor is 17.4 years.

TABLE 4-21. EXAMPLE CALCULATION OF SOLAR HOT WATER SIZING, COST, ENERGY DELIVERY AND COST-EFFECTIVENESS

Hot water use information		**Metric**	**English**
Q_{load}	Building hot water energy requirement	165 kWh/day	0.56 million Btu/day
$\eta_{thermal}$	Thermal efficiency of conventional heating system	0.98	
Stipulated design values			
η_{solar}	Efficiency of solar water heater	0.3	
% Utilization	Fraction of maximum delivered heat that can be used.	0.9	
From map or table			
$I_{C,max}$	Maximum daily solar insolation on tilt = latitude. Table 4-19	6.1 kWh/m^2/day	1934 Btu/ft^2/day
$I_{C,ave}$	Average daily solar insolation on tilt = latitude. Table 4-19	5.5 kWh/m^2/day	1744 Btu/ft^2/day
$\boldsymbol{A_C}$	Area of solar collector Equation 4-46	90.2 m^2	943 ft^2

Calculated energy results

Q_{solar}	Solar heat delivery Equation 4-49	48,871 kWh/year	167 millionBtu/year
Q_{load}	Annual energy to heat water Equation 4-44	54,203 kWh/year	185 millionBtu/year
SF	Fraction of load provided by Solar $SF = Q_{solar}/Q_{load}$	0.90	
$Q_{FuelSavings}$	Savings in heating fuel Equation 4-50	49,868 kWh/year	170 millionBtu/year
Q_{pump}	Parasitic pump energy Equation 4-33	1,069 kWh/year	4 millionBtu/year

Economic results

$C_{initial}$	Initial cost of solar heating system Table 4-17	\$129,866 US dollars	
$C_{savings}$	Annual energy cost savings \$0.18/kWh * ($Q_{savings} – Q_{pump}$)	\$8,784	
$C_{O\&M}$	Annual operation and maintenance cost 1/2% of initial cost per year	\$649	
SPB	Simple payback period; $C_{initial}/(C_{savings} – C_{O\&M})$	16.0	
SIR	Savings-to-investment ratio Equation 4-53	1.09	

We find that under the set of assumptions in this example, a solar water heating system for this laundry facility would meet 90 percent of the load, have a simple payback period of 16 years and a savings-to-investment ratio of 1.09. Since the present value of the life-cycle savings exceed the investment (SIR > 1), we deem the project considered in this example to be cost-effective.

SYSTEM THERMODYNAMICS AND COMPUTER TOOLS FOR ANALYSIS OF SOLAR WATER HEATING SYSTEMS

The equations governing heat flow into and out of the components of a solar water heating system are described along with descriptions of each component in the preceding pages. The first law of thermodynamics (conservation of energy) is written for each component, and this includes fluid flowing in at one temperature and out at another calculated temperature. But if we go around the whole loop, from collector inlet to collector outlet, to heat exchanger inlet, to heat exchanger outlet, to pipe inlet, to pipe outlet, and all the way around back to collector inlet, we find that we have a circular reference. In order to solve for any one of the temperatures, and subsequently all the temperatures, we need to get the number of unknowns equal to the number of equations. The unknowns are the outlet temperatures of each component (which is the inlet temperature to the next component), and the equations are the first law of thermo (energy in = energy out) for each component. Thus we write a system of simultaneous equations, and each equation is the energy balance on a component. There are four ways in which to solve this system of simultaneous equations and find out the equilibrium temperatures (the set of component outlet temperatures which satisfy the energy balance): (1) substitution, (2) Gaussian elimination,(3) matrix inversion, and (4) iteration. The first two are hand techniques and not used to solve this problem. The second two, matrix inversion and iteration, are both computationally intensive and lend themselves to a computer. To use iteration, guess a value for the collector inlet temperature, calculate collector outlet temperature, calculate from pipe heat loss the heat exchanger inlet temperature, calculate from heat exchanger effectiveness the heat exchanger outlet temperature, calculate by pump power and efficiency the outlet temperature of the pump, calculate by pipe heat loss the inlet temperature to the collector. Does the calculated collector inlet temperature match the guess for collector inlet temperature that we started with? If not, guess a higher or lower value and iterate until they do match.

Computer programs use iteration to solve for the system temperatures and heat flow rates at each time interval, and the ending condition of the previous time interval becomes the starting condition for the next time interval in a time series simulation. This method of simulating the performance of a solar water heater was pioneered by researchers at University of Wisconsin at Madison, the University of Waterloo, Waterloo, Canada, and Colorado State University in the 1980s, and the TRNSYS computer program remains a workhorse for consultants that provide simulation of solar hot water systems, although other programs have become available.

A comparison of computer simulation programs is provided based on review of on-line tools directories (DOE OBT 2011), interviews with practitioners, and funding agencies, and involvement or experience of the author. This comparison is certainly not inclusive of all programs available and is not intended to indicate that one is any better than another, rather that each has appropriate applications. Where possible I've used the developers own description of their tool. The programs are compared according to the following criteria:

- Nonproprietary: computer program should be available to competing commercial interests.
- Calculations may be checked: calculations which are used to generate the results should be visible in a spreadsheet form or well-described in program documentation.
- Climate data: extensive weather data for multiple countries or access to climate data is facilitated.
- Well tested: computer program used on many projects to vet bugs and ensure usefulness and confidence in the results.
- Cost: free or low cost.
- User support: contact information is valid and support and training are available.
- Recently updated: program is reflective of current models and computer systems.
- Documentation: complete reference material is available.

A short description is provided for each tool along with other information including expertise required, users, audience, input, output, computer platforms, programming language, strengths, weaknesses, technical contact, and availability.

TABLE 4-22. COMPARISON OF COMPUTER SOFTWARE PROGRAMS FOR DESIGN AND ANALYSIS OF SOLAR WATER HEATING SYSTEM PERFORMANCE.

	Nonproprietary	Visible or well-described calculations	Extensive weather data	Well tested	Free or low cost	User support	Recently updated	Documentation
FEMP Solar Hot Water Calculator	*			*	*	*	*	*
F-Chart	*			*		*		*
FRESA	*				*			*
Polysun				*		*	*	*
REO		*		*			*	
RETScreen	*	*	*	*	*	*	*	*
Solar-Estimate. org				*	*	*	*	
Solar Fraction Calculator for Rated Systems (OG300)		*	*			*		
SolarPro 2.0	*			*		*	*	
SolDesigner	*			*		*	*	
Sol-Opt	*			*	*	*	*	*
T*SOL	*			*		*	*	*
TRNSYS	*	*		*		*	*	*

F-Chart

F-Chart was one of the first tools and has been very useful in estimating savings form solar water heating systems for many years. I think it is a correlation of TRNSYS results against carefully constructed combinations of system parameters. Collector types: flat-plates; evacuated-tubes; parabolic troughs; one- and two-axis tracking. System types: water storage heating; pebble bed storage heating; building storage heating; domestic water heating; integral collector-storage domestic hot water; indoor and outdoor pool heating; passive direct-gain; and passive collector-storage wall.

- Expertise required: Requires training on the data collection and analysis process.
- Users: Unknown, but very many.
- Audience: Engineers.
- Input: Climate data; detailed solar system properties.
- Output: Energy delivery by solar hot water systems.
- Computer platform: Windows 2000.
- Strengths: Sound form of correlation. Detailed system models.
- Weaknesses: Limited to predefined system types.
- Contact: F-Chart Software; Box 44042; Madison, WI, 53744; Telephone: 608-255-0842, Fax: 608-255-0841; Email: info@fchart.com.
- Cost: $400 License fee.

FEMP Solar Hot Water Calculator

Online tool to help federal agencies meet Energy Independence and Security Act (EISA) of 2007, Section 523 requirements for new federal buildings and major renovations to meet 30 percent of hot water demand using solar hot water equipment if life-cycle is cost-effective.

- Expertise required: No special skills required.
- Users: Unknown, rather new tool.

- Audience: Energy management staff at federal sites.
- Input: Location, hot water use, energy cost.
- Output: Energy delivery, cost savings, carbon emissions savings, payback period.
- Computer platform: Web-based application.
- Strengths: Built-in climate data and utility rates.
- Weaknesses: Not specific to system type or performance parameters.
- Contact: National Renewable Energy Laboratory andy.walker@nrel.gov.
- Website: apps1.eere.energy.gov/femp/solar_hotwater_system/index.cfm.
- Cost: Free.

FRESA

FRESA is used to identify and prioritize renewable project opportunities for subsequent feasibility study. Technologies represented include: active solar heating, active solar cooling, solar hot water, daylighting with windows, daylighting with skylights, photovoltaic, solar thermal electric (parabolic dish, parabolic trough, central power tower), wind electricity, small hydropower, biomass electricity (wood, waste, etc.), and cooling load avoidance (multiple glazing, window shading, increased wall insulation, infiltration control). Life-cycle cost calculations comply with 10 CFR 436.

- Expertise required: Must be able to gather summary information on building and installation energy use patterns; intended for use by trained auditors; results should be interpreted by someone familiar with the limitations of the program.
- Users: 50 contractors under the SAVEnergy Audit Program administered by US Department of Energy Federal Energy Management Program.
- Audience: Building energy auditors.
- Input: Summary energy load data; solar and wind resource data provided in a database indexed by ZIP code; biomass and solid waste resource data must be gathered by the auditor.
- Output: Annual cost and energy savings; life-cycle economics; an early indicator if an option is viable; viable options ranked by savings-to-investment ratio.
- Computer platform: PC-compatible, web-based application.
- Programming language: Web-based application.
- Strengths: Establishes consistent methodology and reporting format for a large number of audits in varying locations and with varying building use types; sophisticated analyses of technology performance and cost while keeping data requirements to a minimum.
- Weaknesses: Provides only first-order screening, to focus design; requires more detailed feasibility analyses on applications most likely to be cost-effective; requires high level of knowledge about energy audits and the limitations of the program; not suitable for general use.
- Contact: Dan Olis, National Renewable Energy Laboratory; dan.olis@nrel.gov; National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401, United States.
- Website: https://www3.eere.energy.gov/femp/fresa/.
- Cost: Free.

Polysun

Polysun 4 is renewable energy system simulation software to configure and optimize solar and heat pump systems. Yield-forecasts generated from integrated meteorological data. Detailed models of the systems within the simulation software for system optimization and system comparisons.

- Expertise required: No special computer skills required.
- Users: Approximately 20,000 users internationally.
- Audience: Engineers, designers, component manufacturers.
- Input: Geographic location, component characteristics, energy load profile, costs for economic evaluation, horizon characteristics.
- Output: Output information: Solar fraction, hourly energy usage for system and components, economic analysis, et al.
- Output form: Tables of system and component performance data, customizable on-screen graphs and a preformatted PDF report with system design and performance
- Computer platform: Windows Vista, XP, 2000, NT; at least 512 MB RAM; Internet connection.
- Programming language: Java.
- Strengths: Large customizable component catalog. Quick simulation time (typically less than 2 minutes). Especially good for solar thermal simulation and heat pump simulation.
- Weaknesses: PV is limited to grid-tie systems.
- Contact: Solar Consulting, 33 Water Mill Road, Marion, VA, 24354; Telephone: 703-677-0581, Fax: 703-783-2399; Email: info@solarconsulting.us.;Website: www.solarconsulting.us/polysun.html.
- Cost: Demo is free; Light $130.00; Professional $780, Designer $1950.00; Educational $130 (restrictions apply).

Renewable Energy Optimization

Renewable Energy Optimization (REO) is a program to evaluate life cycle cost of a combination of renewable energy technologies at a site (see an example of output in Table 4-23). Combines resource data and incentive data from other databases, combines simple heuristic estimates of cost and performance.

- Expertise required: Knowledge of energy data and units.
- Users: very few NREL staff providing planning services.
- Audience: Renewable Energy Project Planners.
- Input: GIS data on renewable energy resources via www.nrel.gov/gis. Incentives data from dsireusa.org; cost and performance of each renewable energy technology; site data including square footage of each building type and utility bill information.

TABLE 4-23. EXAMPLE OF REO-GENERATED SPREADSHEET SHOWING RESULTS FOR SOLAR WATER HEATING

	Hot Water Use (gallon/day)	Hot Water Load (therms)	Solar Water Heater Size (ft^2)	Heat Delivery (therms/year)	Pump Energy (kWh/year)	Initial Cost ($)	Fuel Savings (therms/year)	Utility Cost Savings ($)	O&M Cost ($)
Annual total	245,318	788,796	175,260	360,591	(481,508)	$14,962,500	515,130	$382,278	$74,813
January	245,318	80,253		23,084	(30,824)		32,977	$30,420	
February	245,318	73,121		26,116	(34,873)		37,308	$30,715	
March	245,318	78,174		32,967	(44,022)		47,095	$26,813	
April	245,318	70,311		33,442	(44,656)		47,775	$32,644	
May	245,318	65,877		34,878	(46,574)		49,826	$43,621	
June	245,318	57,732		35,299	(47,135)		50,426	$44,165	
July	245,318	55,660		37,686	(50,323)		53,837	$43,814	
August	245,318	54,958		35,516	(47,425)		50,737	$41,933	
September	245,318	55,876		32,977	(44,035)		47,110	$30,477	
October	245,318	63,258		27,540	(36,775)		39,343	$25,147	
November	245,318	67,776		20,663	(27,591)		29,518	$13,439	
December	245,318	65,801		20,424	(27,273)		29,177	$19,089	

- Output: Energy delivery by renewable energy systems, initial cost, O&M cost, life-cycle cost. All outputs are in Microsoft Excel tables and are copied to a Microsoft Word report.
- Computer platform: Windows 2000, XP, Vista. MS Excel spreadsheet. MS Visual Basic version under development.
- Programming language: Excel, Premium Solver by Frontline Systems.
- Strengths: Efficient processing of site data to identify and prioritize project opportunities.
- Weaknesses: Simple heuristic algorithms; No full engineering feasibility study.
- Contact: Andy Walker, National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401-3393; Telephone: 303-384-7531; Email: andy.walker@nrel.gov; Website: www.nrel.gov.
- Cost: Free for government-use license only.

RETScreen

Natural Resources Canada provides software for evaluating energy production and savings, costs, emission reductions, financial viability, and risk for various types of renewable-energy and energy-efficient technologies. The software (available in multiple languages) includes product and resource information, a detailed user manual, and a case study based college/university-level training course, including an engineering textbook.

- Expertise required: None; training material included in software.
- Users: More than 135,000 worldwide in 222 countries.
- Audience: Engineers, architects, technologists, planners, facility managers, and educators.
- Input: Project dependent input in spreadsheet format. Climate data and product data included in software. Default and suggested values for all inputs via manual or project database.
- Output: Energy balance, emission analysis, financial analysis, etc. All outputs are in Excel and can be copied, printed, or saved to PDF format.
- Computer platform: Windows 2000, XP, Vista.
- Programming language: Excel, Visual Basic, C#.
- Strengths: Easy completion of feasibility studies for renewable energy and energy efficiency technologies.
- Contact: Natural Resources Canada, CANMET Energy Technology Centre-Varennes, 1615 Lionel-Boulet, P.O. Box 4800, Varennes, Quebec J3X 1S6, Canada; Telephone: 450-652-4621, Fax: 450-652-5177; Email: rets@nrcan.gc.ca; Website: www.retscreen.net/.
- Cost: Free.

Solar-Estimate.org

Online software tool with calculators for PV, domestic hot water, and pool/spa heating to determine the costs and benefits of solar energy systems for a particular location and building needs. Links and resources to current information about solar energy data and programs.

- Expertise required: No special expertise required.
- Users: More than 2,500.
- Audience: Contractors, building owners, consultants, architects, engineers. Covers many professional services related to renewable energy and energy efficiency.
- Input: Location (state and country), energy usage (PV), water usage (domestic hot water), pool/spa size, utility, building type (residential or commercial/business). Many parameters have defaults but can be overridden by the user.
- Output: Results and information to the Web browser screen. Can be printed and copied/pasted.
- Computer platform: Any Web browser.
- Programming language: PHP and MySQL databases.
- Strengths: Initial sizing and financial estimates for solar energy systems, including applicable incentive and tax credits.
- Weaknesses: Does not do detailed sizing or quoting of solar energy systems. Data covers United States only.
- Contact: Solar-Estimate.org, P.O. Box 4352, Santa Rosa, CA 95402-4352, United States; Telephone: 707-237-5204; Email: scott@energymatters.net; Website: www.solar-estimate.org.
- Cost: Free.

SolarPro 2.0

Simulates the operation of an active solar hot water heating system, hour by hour, for one year, based on Typical Meteorological Year 2 (TMY2) climate data. Dozens of variables in the simulation can be changed by the user.

- Expertise required: General knowledge of solar thermal processes.
- Users: New software product.
- Audience: Solar design engineers, solar contractors, do-it-yourselfers.
- Input: Main inputs required: TMY2 data file of 239 U.S. locations provided on the CD-ROM, solar collector OG-100 panel ratings (database included), tank size and insulation factor, customer hot water use pattern.
- Output: Solar fraction, hourly charts, hour-by-hour simulation end points in spreadsheet format, etc.
- Computer platform: Windows 95.
- Programming language: Visual Basic.
- Strengths: Detailed, accurate simulation.
- Weaknesses: Level of user input can be cumbersome.
- Contact: Telephone: 808-875-0110; E-mail: sandy@maui.net; Website: http://www.mauisolarsoftware.com/
- Cost: $125 for Solar Hot Water; $249 for complete solar software suite

SolDesigner

A design system for the detailed hydraulic and control design of solar thermal systems. SolDesigner is useful for finding solutions for hot water and solar heating of buildings and pools. SolDesigner produces a design of the solar system and estimates for costs and energy output.

- Expertise required: No special skills necessary.
- Users: Officials, engineers, house-owners, builders, plumbers.
- Audience: Officials, tech-design engineers, house-owners, builders, plumbers.
- Input: Location and orientation, daily hot water demand, and space heating load.
- Output: Collector area, storage volume, energy output estimates.
- Computer platform: Windows-based PC, requires Excel.
- Programming language: Excel spreadsheet.
- Strengths: Detailed design of the hydraulic and electrical solar system.
- Weaknesses: Does not give simulated energy yields, rather heuristic estimates. German language versions only.
- Contact: DreSys Regenerative Systeme Magdeburg, Germany; Telephone: +49 (391) 543 1689, Fax: +49 (391) 543 1689; Email: DreSys@foni.net; Website: http://home.foni.net/~can-drescher/LIZENZ.HTM
- Cost: US $25, plus shipping and handling.

SolOpt

Program to help energy auditors evaluate rooftop solar photovoltaics and solar hot water. Hourly simulation to determine the costs and benefits of solar energy systems for a particular location and building needs. Determines optimal use of available roof space.

- Expertise required: Some training required.
- Users: Solar America Cities audit teams.
- Audience: Contractors, consultants, architects, engineers.
- Input: Hourly weather data; hot water use data; economic parameters; solar system properties.
- Output: Cost and savings of optimal combination of PV and solar hot water for a limited roof area.
- Computer platform: Windows PC.
- Programming language: Microsoft Excel; Visual Basic.
- Strengths: Initial sizing and financial estimates for solar energy systems, including applicable incentive and tax credits. Detailed algorithms; 8760 Simulation.
- Contact: National Renewable Energy Laboratory; 1617 Cole Blvd; Golden, CO 80401; Telephone: 303-275-3000; Email: ian.metzger@nrel.gov; Website: http://www4.eere.energy.gov/solar/sunshot/resource_center/resources/solopt_optimization_tool
- Cost: Free

System Advisor Model (SAM)

SAM is based on TRNSYS and models residential or commercial solar water heating systems. Evaluates several different types of financing to represent both residential, commercial, and third-party financed systems. Solar water heating model is closed-loop, two-tank system and allows user to vary climate data, water heating system costs, and characteristics of the collector, storage, and heat exchanger. Categories of cost are added up to calculate levelized cost of energy ($/kWh) as the figure of merit.

- Expertise required: One to two days of training recommended.
- Users: More than 3,000.
- Audience: Feasibility studies and policy-making, consultants, engineers. Not intended as engineering tool.
- Input: Weather data (TMY-2 in EPW format), utility rate structure, financial assumptions, incentives, component parameters, costs.
- Output: Financial metrics: levelized cost of energy, rate of return, payback period. Graphs and reports. Cash flow detail and hourly data may be exported to Excel spreadsheet.
- Computer platform: Windows 7/Vista/XP or OS X 10.6 Intel or later; 500 MB disk space.
- Programming language: TRNSYS engine.
- Strengths: Detailed time series simulation models details of hourly load profile and other conditions. Provides financial estimates for solar water heating systems, including applicable incentive and tax credits. Sensitivity analysis.
- Weaknesses: Not intended as engineering tool, requires user to specify details of the design.
- Contact: System Advisor Model Website: https://sam.nrel.gov/ Email: Solar_Advisor_Support@nrel.gov.
- Cost: Free.

T*SOL

Software for the planning, analysis, and simulation of thermal solar heating systems. T*SOL can also be used for education purposes by universities and research institutes. A large number of solar water heating systems, including space heating and pool heating, can be evaluated under varying parameters, with the results (temperature, energies, efficiencies, and solar fraction) easily saved to a file and presented in graph or chart form.

- Expertise required: No special expertise needed.
- Users: Over 1,000 users in Germany, Austria, and Switzerland. Now available internationally with the English version 4.0.
- Audience: Professionals: solar specialists, planners, engineers, heating technicians and plumbers, energy consultants. Educators: universities and research institutes.
- Input: Collector area, regulating temperatures, costs, consumption, storage tank size, and heat exchanger.
- Output: Preformatted reports in graph and chart form. User-definable reports also possible. Economic efficiency calculation.
- Computer platform: Windows 95, 98, NT, or 2000, 166 MHz Pentium PC, 32 MB RAM, 50 MB hard disk space, CD and floppy disk drives.
- Programming language: Borland Pascal.
- Strengths: Precise calculations possible, very user-friendly, no training required.
- Contact: Valentin Software Inc., Temecula, CA ; Telephone: (951) 530-3322; Fax: (858) 777-5526; Email: info@valentin-software.com; Website: www.valentin-software.com.
- Dr. Valentin EnergieSoftware GmbH, Stralauer Platz 33-34, Berlin D-10243, Germany; Telephone: +49 (30) 588 439-0, Fax: +49 (30) 588-439-11; Email: info@valentin.de; Website: www.valentin.de.
- Cost: Basic Pro $980; Expert $1,980

TRNSYS

A detailed energy simulation program with a flexible modular system approach. TRNSYS (TRaNsient SYstem Simulation Program) includes a graphical interface, a simulation engine, and a library of components that range from various building models to standard HVAC equipment to renewable energy and emerging technologies. TRNSYS also includes a method for creating new components that do not exist in the standard package.

- Expertise required: None to use standard package; FORTRAN knowledge helpful for developing new components.
- Users: Over 500.
- Audience: Engineers, researchers, consulting firms, architects.
- Input: Detailed building input description, characteristics of system components and the manner in which components are interconnected, and separate weather data. Input files can be ASCII text or can be generated by using a graphical user interface known as the Simulation Studio.
- Output: Life cycle costs; monthly summaries; annual results; histograms; plotting of desired variables (by time unit). It is also possible to plot variables as the simulation progresses.
- Computer platform: Windows 95 or higher (98, NT, 2000, ME, etc.) for TRNSYS interface programs (distributed source code will compile and run on any FORTRAN platform).
- Programming language: FORTRAN (although unnecessary for the use of standard components). It is also possible to write components in C++.
- Strengths: Modular approach and component library. Very detailed models. Extensive documentation. Graphical interface to drag-and-drop components for creating input files (Simulation Studio)
- Weaknesses: No assumptions about the building or system are made (although default information is provided),

so the user must have detailed information about the building and system and enter this information into the TRNSYS interface.

- Contact: Solar Energy Laboratory, University of Wisconsin, 1500 Engineering Drive, Madison, WI 53706, United States; Telephone: 608-263-1589, Fax: 608-262-8464; Email: trnsys@sel.me.wisc.edu; Website: sel.me.wisc.edu/trnsys.
- Cost: Version 16, for commercial use $4,200; educational use is $2,100.

CODES AND STANDARDS FOR SOLAR WATER HEATERS

There are several organizations that provide certification of solar collector and solar collector system performance, and there are several codes that govern general plumbing and electrical requirements of an installation.

American Society of Civil Engineers (ASCE)

ASCE provides a method for calculating weight, wind and seismic loads on arrays of solar panels and allows for alternative materials and methods that demonstrate the structural integrity of the design.

- ASCE 7 "Design Loads for Building and Other Structures."

American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE).

The standard rating procedures referred here find their origin in the standard ANSI/ASHRAE Standard 93-77 *Methods of Testing to Determine the Thermal Performance of Solar Collectors* (ASHRAE 1977). This testing procedure, published in 1977 by the American Society of Heating, Refrigerating and Air Conditioning Engineers, isolates an optical gains coefficient, a thermal loss coefficient, an incident angle coefficient, and the thermal capacitance of a solar collector. The results of the test give the empirical coefficients of the equations for efficiency and heat delivery as functions of environmental conditions (temperature and insolation). The test apparatus used to conduct the testing is illustrated in Figure 4-29.

ASHRAE also publishes three very useful guides for design, installation, and preparation of operating manuals:

- *Active Solar Heating System Design Manual* (1988)
- *Active Solar Heating System Installation Manual* (1991)
- *Guide for Preparation of Active Solar Heating System Operation and Maintenance Manuals* (1988).

Solar Rating and Certification Corporation (SRCC)

This is the principle rating organization for solar domestic hot water collectors and residential-scale complete systems. The

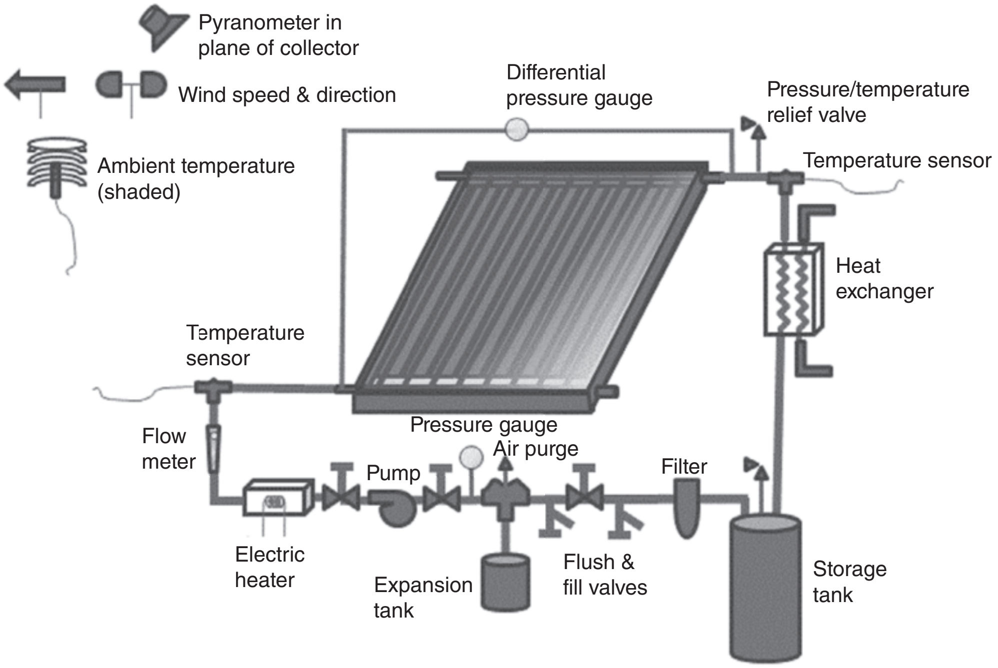


Figure 4-29. Schematic diagram of test apparatus used to correlate performance of solar collectors with measured conditions. (Figure by the author)

SRCC publishes the following standards regarding solar thermal collectors:

- OG-100 *Operating Guidelines for Certifying Solar Collectors*
- Standard 100 *Test Methods and Minimum Standards for Certifying Solar Collectors*
- Standard 150 *Test Methods and Minimum Standards for Certifying Innovative Solar Collectors*
- RM-1 *Methodology for Determining the Thermal Performance Rating for Solar Collectors*
- Standard 600 *Test Methods and Minimum Standards for Certifying Solar Concentrating Collectors*

SRCC publishes the following standards regarding certification of entire systems:

- OG-300 *Operating Guidelines and Minimum Standards for Certifying Solar Water Heating Systems*
- TM-1 Solar *Domestic Hot Water System and Component Test Protocols*

Testing is conducted indoors with temperature maintained by mechanical systems and lights bright and warm enough to simulate sunlight. Testing of solar collectors results in the optical gains coefficient, incident angle modifier, heat loss coefficient, and thermal capacitance of the collector. For complete systems the approach is to combine component testing with system simulation. A hot water demand of 43.3 MJ/day is simulated by six equal water draws each hour from 9:30 a.m. to 2:30 p.m. The sunlight is simulated for 9 hours with a peak of 700W/m^2 at noon. The incident angle is also manipulated 15 degrees per hour with a value of zero at noon. The result of the testing and/or simulation is a solar energy factor (SEF), which is the ratio of the energy delivery divided by the electricity put into the system for pumps, controls, and auxiliary energy needed to meet the load. This relates to solar fraction discussed earlier according to

$$SF = 1 - \frac{1}{SEF} \tag{4-54}$$

Chinese National Centre for Quality Supervision and Testing of Solar Heating Systems

The National Centre for Quality Supervision and Testing of Solar Heating Systems, part of the National Academy for Building Research in Beijing, China, maintains a system of quality supervision and certification for solar thermal collectors and systems. Three testing centers are in Beijing, Wuhan, and Kunming. Chinese standards include minimum certification criteria that must be met if a product or system is to meet the standard. For flat-plate solar collectors the value of $F_R\tau\alpha$ must exceed 0.72 and for evacuated-tube must exceed 0.62. The heat loss coefficient F_RU_l must not exceed 6.0 W/m^2 for flat-plate collectors and must not exceed 3.0 W/m^2 for evacuated-tube collectors. For complete systems with a solar resource of 17MJ / m^2· day, the useful energy collected must exceed 7 MJ/m^2. Reference to Chinese standards start with GB which stands for "GuoBiao," Chinese for "national standard," and are mandatory and promulgated by the Standardization Administration of China. Standards that are recommended but not mandatory start with "GB/T,", the *T* standing for "Tuijian," Chinese for "recommended." Standards related to solar water heating include (He, Zheng, and Zhang 2011):

- GB 50364 (2005) *Technical code for solar water heating system of civil buildings*
- GB 50495 (2009) *Technical code for solar heating system*
- GB/T 18708 (2002) *Test methods for thermal performance of domestic solar water heating systems*
- GB/T 19141 (2003) *Specification of domestic solar water heating systems*
- GB/T 18713 (2002) *Solar water heating systems Design, installation and engineering acceptance*
- GB/T 17049 (2005) *All-glass evacuated solar collector tubes*
- GB/T 19775 (2005) *Glass-metal sealed heat-pipe evacuated solar collector tubes*
- GB/T 20095 (2006) *Assessment code for performance of solar water heating systems*
- GB/T 4271 (2007) *Test methods for the thermal performance of solar collectors*
- GB/T 6424 (2007) *Flat-plate solar collectors*
- GB/T 17581 (2007) *Evacuated-tube solar collectors*

Florida Solar Energy Center (FSEC)

Although a state institution, FSEC advances solar water heating standards regionally and internationally, as well. FSEC publishes collector certifications, administers state solar testing programs, and conducts research for DOE and other sponsors. FSEC publishes:

- FSEC Standard 101-10 *Operation of the Solar Thermal Collector Certification Program*, procedures by which solar collectors are rated for performance, examined for compliance to minimum standards, and certified
- FSEC Standard 102-10 *Test Methods and Minimum Standards for Certifying Solar Thermal Collectors*
- *Solar Water and Pool Heating Manual: Design and Installation & Repair and Maintenance*, January 2006. Florida Solar Energy Center, www.fsec.ucf.edu.

International Association of Plumbing and Mechanical Officials

IAPMO follows the American National Standards Institute's process for involving regulators and industry in developing codes and standards. IAPMO products related to solar water heating include (International Association of Plumbing & Mechanical Officials, www.iapmo.org):

- IAPMO/ANSI USEC 1- 2009 *Uniform Solar Energy Code* (2009)
- UPC *Uniform Plumbing Code* (2009)
- IGC 086-2002 *Passive Solar Water Heaters* (2002)
- IGC 190-2003 *Air Based Solar Thermal Collectors* (2003)

North American Board of Certified Energy Practitioners (NABCEP)

NABCEP issues training and Solar Heating Installer Certification, a voluntary certification that may be required as proof of skill and experience as part of a solicitation (NABCEP 2011).

Occupational Safety and Health Administration

OSHA issues the regulation *Safety and Health Regulations for Construction,* which must be observed in order to satisfy requirements related to workplace and worker safety. There are many hazards involved including falls from heights, soldering with flame, electrical hazards, heat exhaustion and sunburn, and many others, each of which must be identified and mitigated (www.osha.gov).

Unified Facilities Criteria

The Unified Facilities Criteria was established to make construction criteria uniform across the services. The document concerning solar water heating sytems is *Active Solar Preheat Systems: Unified Facilities Criteria* (UFC 3-440-01.pdf), 2007, US Department of Defense, www.wbdg.org.

ASTM International (formerly American Society for Testing and Materials

ASTM (www.astm.org) has perhaps over one hundred standards related to solar. The ones most applicable to solar water heating are produced by Techncial Committee E44 and include:

- E772-05 *Standard Terminology Relating to Solar Energy Conversion*
- E1056085 (2007) *Standard Practice for Installation and Service of Solar Domestic Water Heating Systems for One and Two-Family Dwellings*
- E683-91(2007) *Standard Practice for Installation and Service of Solar Space Heating Systems for One- and Two Family-Dwellings*
- E1106-87 (2007) *Standard Guide for On Site Inspection and Verification of Operation of Solar Domestic Hot Water Systems*
- ASTM D3667-05(2010) *Standard Specifications for Rubber Seals Used in Flat-Plate Solar Collectors*
- E1084-86(2009) *Test Method for Solar Transmittance and Reflectance of Sheet Materials*
- E712-80(2009) *Standard Practice for Laboratory Screening of Metallic Containment Materials for Use with Liquids in Solar Heating and Cooling Systems*
- E744-07 *Standard Practice for Evaluating Solar Absorptive Materials for Thermal Applications*
- E822-92(2009) *Standard Practice for Determining Resistance of Solar Collector Covers to Hail*
- E861-94(2007) *Standard Practice for Evaluation Thermal Insulation Materials for use in Solar Collectors*
- E904-87(2007) *Standard Practice for Generating All Day Thermal Performance Data for Solar Collectors*
- E905-87(2007) *Standard Test Method for Determining Thermal Performance of Tracking Concentrating Solar Collectors*

OPERATION AND MAINTENANCE OF SOLAR WATER HEATING SYSTEMS

Operation and maintenance (O&M) costs for solar water heating system are often estimated at one-half of 1 percent of the initial cost per year. For simple passive systems without pumps and controls let me guess that O&M costs may be on the order of 1/4 of 1 percent of initial cost per year. O&M is similar to that required of any hydronic heating loop and may be provided by site staff, with experts called in if something should fail. Planned operation and maintenance tasks performed by site staff on an on-going basis include:

- Observe operational indicators of temperature and pressure to ensure proper operation of pumps and controls.
- Observe that the pump is running on a sunny day, and not at night.
- Check status indicators of controller faceplate. Compare indicators with measured values.
- Document all operation and maintenance activities in a workbook available to all service personnel.

Planned tasks performed annually by site staff include:

- Check the solar collection tubes and frames for any damage. Note location of broken panes or tubes for replacement.
- Check proper position of all valves.
- Inspect and maintain the pipe insulation and protective materials.
- Check tightness of mounting connectors. Repair any bent or corroded mounting components.
- Determine if any new objects, such as vegetation growth, are causing shading of the array and move them if possible. Remove any debris from behind collectors and from gutters.
- Clean array annually with plain water or mild dishwashing detergent. Do not use brushes, any types of solvents, abrasives, or harsh detergents.
- Check all connecting piping for leaks. Repair any damaged components.
- Check plumbing for signs of corrosion.

Tasks performed by a solar contractor at intervals indicated by site conditions may include:

- Measure incident sunlight and simultaneously observe temperature and energy output. Compare readings with original efficiency of system (every 10 years).
- Flush potable water storage tank to remove sediment (annually).
- Check condition of heat-transfer fluid (freeze point and pH) and replace if depleted or acidic (annual).
- Flush-and-fill replacement of heat-transfer fluid (every 10 years).
- Clean inside heat exchanger to remove mineral scaling (as required).
- Replacement of the sacrificial anode in the storage tank (as required).

In addition to this regularly scheduled maintenance, unscheduled maintenance is required to address component failure. Results of a survey of existing systems (Walker and Roper 1992b) indicate that many systems are disabled by very simple problems which are inexpensive to repair. The study inspected 185 systems: 120 of which were working fine, and 65 of which had been affected by a problem. Systems had been in operation for between 6 and 12 years. One of the most common problems was wires to temperature sensors that have been broken, or temperature sensors that had simply fallen off the surface they were to measure. A pump can be disabled by failure of the starting capacitor or by failure of the pump motor. Leaks can be inexpensive to repair but can cause damage to other building materials and might be expensive to repair if they are caused by a component corroding through. Replacement of glass broken by hail or vandalism is also occasionally required. The sacrificial anode in the tank should be replaced as required and at some point in time (typically in excess of 10 years) the storage tank may need to be replaced. Figure 4-30 shows the relative frequency of the problems identified in the survey.

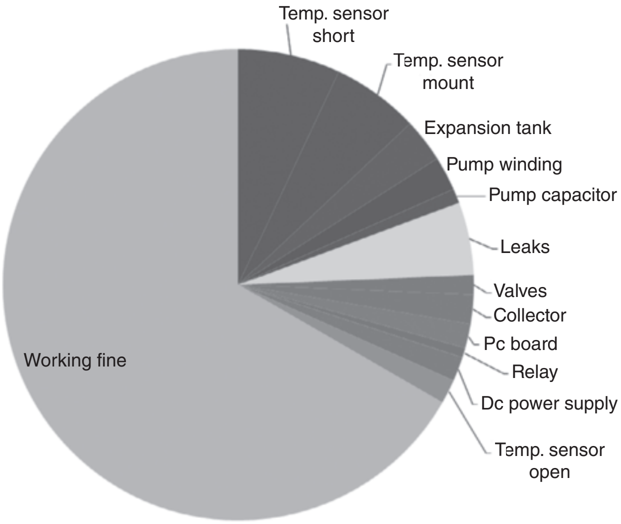


Figure 4-30. A survey of 185 solar water heating systems identified common problems, many of which are easy to fix. (Figure by the author)

CASE STUDIES OF SOLAR WATER HEATING SYSTEM INSTALLATIONS

Here we consider two case studies, one at either extreme of the size range: a small residential system and a large central-plant system.

Direct, Active Residential Solar Water Heating Systems in Hawaii

High energy costs and a uniform solar resource make Hawaii a good location for cost effective applications of solar water heating. Sixty-two solar water heaters were installed on government-owned housing in Honolulu in 1998. Due to the nonfreezing climate, the systems are direct, active, open loop systems with a single tank (electric water heater with the bottom element disabled). This approach relies on stratification within the storage tank to send the coldest water available from the bottom of the tank to the solar collectors.

Tiny Hobo data loggers from Onset Computer Corp. were used to measure the on/off cycles of the electric water heating elements before the systems were designed; and the same technique was used to measure the savings after the systems were installed (Walker, Christensen, and Yanagi 2003). The hot water energy use averaged $Q_{load} = 11.2$ kWh/day or 4088 kWh/year per house. Each house is provided with two Model AE-32E solar collectors manufactured by Alternate Energy Technologies Inc. The collectors are single glazed, selective surface on copper absorber plate, each of $A_C = 3$ m^2 (31.9 ft^2) area. The optical gains fraction of the efficiency equation reported in the SRCC rating is $F_R\tau\alpha = 0.739$ and the thermal loss coefficient is $F_RU_L = -5.53$ W/m^{2}C. Potable water is circulated by a Taco model 006-BC-1 pump drawing 0.52 Amps at 115 V. The pump is controlled by a Heliotrope General model DTT-94 differential temperature controller with a high temperature limit switch set to 70 C (160 F). Storage tanks are 120 gallon insulated with two inches of polyurethane foam manufactured by American Water Heater Group. Hawaiian Electric Company provided quality standards, design review and technical assistance throughout the project, and shared the cost with the $800 per system rebate. The systems were designed and installed by Pacific Mechanical Company. Figure 4-31 shows the rooftop installations.

In 2003, instruments were installed to measure on/off cycles of the electric water heaters and the tank outlet temperature on 25 of the houses with solar water heating and 25 identical houses without solar. Measurements shown in Figure 4-32 indicate an annual electric demand savings of 1.62 kW/house

Figure 4-31. Photograph of four of the direct, active, residential solar water heating systems in Honolulu, Hawaii, described in the case study example. (Photograph by the author)

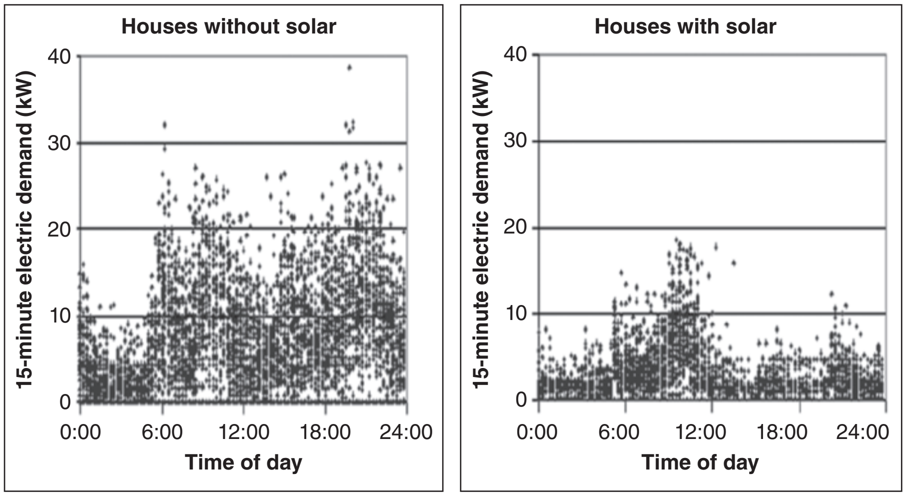
and an annual energy savings of $Q_{savings}$ = 3,008 kWh/house/year. The solar fraction is SF = 74 percent and the solar system efficiencies average η_{solar} = 25 percent per year. Efficiency is lower than the 30 percent to 40 percent expected of many systems (Christensen and Barker 1998), perhaps because the single tank gets mixed by the circulation of water through the solar collectors, and causes the collector to operate at a higher temperature than the incoming cold water temperature. Annual cost savings is estimated at $C_{savings}$ = \$380/house/year averaged over all the measured houses. For a per-system cost of C_{intial} = \$3,200 (\$4,000 minus a \$800 utility rebate) the simple payback period is 8.4 years and using a present worth factor of 17.1 years (25-year analysis period and 4 percent discount rate), the savings to investment ratio (SIR) is 2.03.

Indirect, Active Large Central-Plant Solar Water Heating System in Arizona

Ken May, founder of Industrial Solar Technology (IST) Corp., approached a prison north of Phoenix, Arizona with an interesting proposal. IST offered to install a solar water heating system at its expense, to operate it over a period of 18 years, and to sell the prison heat at a rate of 90 percent of the cost that the utility was charging for the same amount of electric energy (Walker and Dominick 2000). IST had identified the prison as a good candidate because:

- The prison was in an area of high direct-beam solar insolation (I_C = 5.2 kWh/m^2/day for one-axis tracking).
- It had relatively expensive electricity as its source of heating energy.
- Its hot water load was daily without interruptions for weekends or holidays.

I went around with an inmate electrician to install data loggers and measured the prison water heating energy load to be Q_{load} = 3,408 kWh/day in 1994, and the system was designed to provide slightly more than that. The system is installed on 1.2 acres of land adjacent to the prison. Hot water is delivered to the prison buildings through almost two miles of insulated underground piping, installed with supply, return, insulation, and protective jacket in one assembly. The solar array consists of 120 parabolic trough solar collectors totaling A_C = 1,584 m^2 (17,040 ft^2) in area. Storage of $M_{storage}$ = 87,000 kg (23,000 gallons) is provided in two above-ground unpressurized



Houses without solar

Houses with solar

Figure 4-32. Data collected from 25 houses with solar water heaters and 25 identical houses without solar water heaters, indicating the savings in electric-heater power consumption delivered by the solar systems. (Figure by the author)

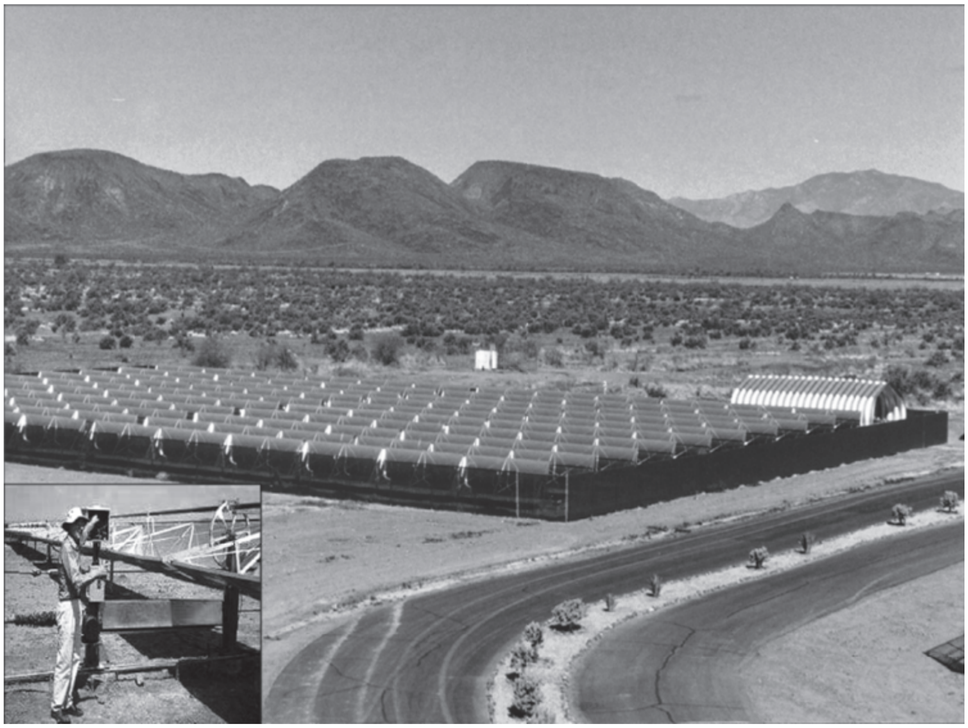


Figure 4-33. Photograph of 1,584 m^2 (17,040 ft^2) active, indirect central-plant solar water heating system at a prison north of Phoenix, Arizona, described in the case study example. The metal building in back houses the storage tanks, pumps, and controls. (Photograph provided by Ed Hancock)

storage tanks that were built on-site with frames made of steel and plywood and a liner and were protected in a steel shed, which also houses pumps and two energy meters. Propylene glycol/water heat-transfer fluid circulates between the solar array and through heat-exchanger coils submerged in the bottom of each of the storage tanks. Each of the tanks has nine coils of 3/4-inch copper pipe, each 60 feet long for a total heat exchanger area of 21 m^2 (228 ft^2). Similarly, potable water is heated as it flows through ten coils in the top of each tank with a total area of A_{hx} = 31 m^2 (332 ft^2). Tempering valves maintain a hot water delivery temperature of T_{del} = 55C (132F).

The system was installed in 1998. Figure 4-33 shows the system, including both the solar array and the building that encloses the storage tank. The system delivered Q_{solar} = 1,161,803 kWh its first year of operation. This saved the prison $C_{savings}$ = \$77,805 in utility costs, of which \$70,025 was in turn paid to IST, the performance contractor, for a net savings to the prison of \$7,780/year. The efficiency of the system over this first year was approximately η_{solar} = 39 percent and the solar fraction was approximately SF = 93 (May et al 2000). The installed cost of the system is reported to be $C_{initial}$ = \$650,000, for a simple payback period of 8.3 years and a savings-to-investment ratio of SIR = 2.1 (using a preset worth factor of 17 years (25-year period at 4 percent discount rate). The monthly energy delivery measured throughout five years of monitoring is shown in Figure 4-34. In October 2002, a pump failure also led to failure of many of the absorber tube assemblies due to high temperatures. By January 2003 the contractor had repaired the damage, and the system continued to deliver cost and environmental benefits.

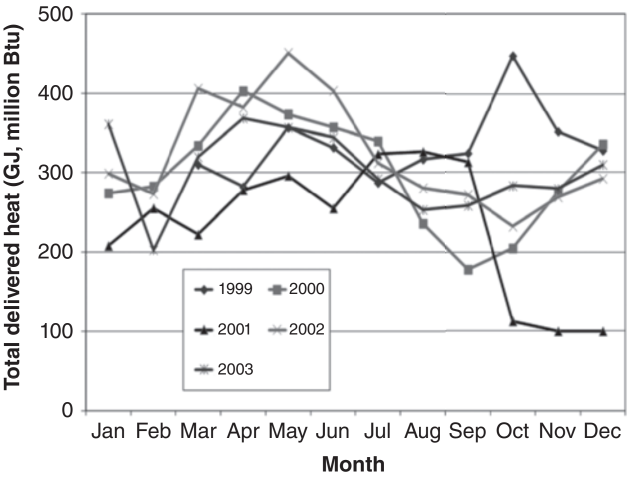


Figure 4-34. Data collected from 1999 to 2003 reports energy delivery of the large central solar water heating system, including a problem in October 2001 that was rectified by January 2002. (Figure by the author)

Example

Procurement Specifications for a Solar Water Heating System

The following text is a sample of procurement specifications typical of what might be issued in a request-for-proposals or subsequently in a contract for design and construction. These specifications were originally published by the US Department of Energy Federal Energy Management Program in 2003 (no longer posted on their website), and subsequently updated by the author based on project preparation and input from vendors. These specifications are probably not inclusive of all the considerations that must be addressed in your particular project. These are offered only as encouragement that you can get your requirements down on paper and to give you a head start on that task.

Part 1: General

Summary

This section specifies design, provision, installation, and commissioning of a complete, operational and code-compliant solar water heating system as described herein and on the associated drawings. The solar water heating system includes: roof attachments and support structure; solar collectors; pumps; controls and additional instruments and monitoring system; pipe; valves; heat exchangers; heat-transfer fluid; insulation on all pipe and components; tempering mixing valve, flush-and-fill valves, pressure relief valves, and all other appurtenances to make the solar water heating system complete and operational.

Description of Work

The scope of work includes all labor, supervision, equipment inside and outside the building, tools, materials and incidentals necessary to design, procure, install, checkout and place into operation a complete solar water heating system ready for use for the building. Contractor shall provide all construction management and supervision as well as administration of the construction contract. Contractor shall meet periodically with building management.

The contractor shall provide all professional services to provide a complete design package addressing the requirements of this specification. The design package shall include design narrative, specifications, calculations, and drawings. After approval of the design by entities having responsibility for aesthetics, safety, security, and building roof, plumbing and electrical systems, the contractor shall provide all materials, supplies, equipment, and construction services to install and commission the complete and operational solar water heating system.

The project location is <fill in building name here>, at <fill in address here>. Design and installation must satisfy all performance requirements including: hot water use requirements; structural requirements; potability and safety requirements; and thermal performance heat gain requirements. A single contractor shall be responsible for the design, installation, and commissioning of the system. The contractor shall coordinate with all authorities having jurisdiction and obtain on the building owner's behalf all required permits including those related to building codes and inspections, roof integrity and maintenance of roof warranty, historic preservation or other cultural resources; safety and security; and any other imposed requirements that may influence the selection of locations, materials, equipment, and installation procedures.

Related Documents/Sections

Applicable provisions of electrical and plumbing specifications govern work under this section.

References

The publications listed below form a part of this specification to the extent that they pertain to the subject project. The publications are referred to in the text by the basic designation only.

- American Society of Civil Engineers (ASCE): SEI-7 Minimum Design Loads for Buildings and Other Structures
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc (ASHRAE): ASHRAE 90003 Active Solar Heating Design Manual; ASHRAE 90336 Guidance For Preparing Active Solar Heating Systems Operation and Maintenance Manuals; ASHRAE 90342 Active Solar Heating Systems Installation Manual; ASHRAE Methods of Testing to Determine the Thermal Performance of Solar Collectors
- American Society of Mechanical Engineers: Boiler and Pressure Vessel Code (unless tanks fall into one of the classes exempt from the standard)
- American Water Works Association (AWWA) C651 Disinfecting Water Mains
- Factory Mutual Engineering and Research Corporation (FM): FM P7825 Approval Guide-Fire Protection Tests for Solar Component Products
- International Association of Plumbing and Mechanical Officials (IAPMO): Uniform Solar Energy Code Safe Solar System Requirements (2006)
- Lighting Protection Institute: Roof lightning protection guidelines.
- National Fire Protection Association (NFPA): NFPA 70 National Electrical Code
- National Roofing Contractors Association (NRCA): Roofing Guidelines (written for photovoltaics but also applicable to solar hot water)
- Occupational Health and Safety Administration: Any related to workplace and worker safety

(continued)

- Sheet Metal and Air Conditioning Contractors: National Association HEET Guidelines related to metal work including ductwork, sealing through-penetrations and fire-stopping.
- Solar Rating and Certification Corporation (SRCC): OG-300-08 Operating Guidelines and Minimum Standards For Certifying Solar Water Heating Systems; OG-100-06 Operating Guidelines for Certifying Solar Collectors

Design Requirements

Design new solar water heating (SHW) systems for the heating of domestic water. The solar water heating system offsets the use of conventional fuels by preheating water before the conventional domestic hot water system. Construction documents shall be signed and sealed by an engineer licensed to practice within the jurisdiction. Design and installation shall comply with all applicable codes and standards including but not limited to plumbing, electrical, structural, wind, snow, and seismic requirements. Calculations are to be based on the parameters obtained through authorities having jurisdiction or referenced engineering resource: minimum force per area; design wind speed (m/s or mph); wind exposure class; seismic requirements; lightning protection and any other requirements that must be satisfied to comply with codes and meet all regulatory requirements.

Component and material selection should be made to obtain a minimum 40-year design life.

Products used (electrical and mechanical components) shall be listed by UL, FM, ETL, or other recognized testing laboratory. Any nonlisted products proposed shall be identified as such and approved by the building management prior for use in construction. It is the intent to exhibit this feature of the building to visitors, so appearance and quality are considerations in design decisions.

Solar collectors are to be mounted on the roof or on the ground as suitable for the type of SHW system and needs and limitation of the building and site. Areas around the SHW system for personnel to walk where needed, and an area around the perimeter of the roof eves and gable ends shall be kept clear as required for people working on the roof, building codes, fire codes, or building management. The collector system, including supports and piping, shall not interfere with roof drains, expansion joints, air intakes or exhaust hoods, antennas, or any other existing equipment on the roof. Design shall minimize roof penetrations and take measures to seal any required penetrations. Pipe penetrations through other building fabric (walls, floors) shall be minimized.

Collectors shall be of a type suitable for the application and have performance characteristics (heat loss) appropriate for the temperatures developed in the type of system proposed. The pressure rating of the collector shall be appropriate for the type of overheat protection and maximum pressures expected. Contractor shall furnish and install a rack mounting system with the appropriate tilt to optimize solar delivery, but within any constraints of aesthetics and shading. All solar collectors in the same row must be oriented in the same plane.

System must be of a type suitable to the climate of the site and the water heating application. System types incorporating both freeze-protection and overheat protection are required. Freeze protection is not required if climate is nonfreezing, but overheat protection required in all systems. Supplied equipment must be rated and warranted to withstand and operate under lowest-record-low and highest-record-high temperature for the location. System must be able to withstand prolonged periods of no hot water demand (stagnation conditions) without system deterioration and without operator intervention.

The solar system is to incorporate the existing conventional water heating system as its auxiliary subsystem. In the event that the existing water heater is in need of repair or replacement, the contractor may propose to repair or replace the electric water heater under the scope of this project. The solar system shall be connected to and operated in conjunction with the existing water heating system in such a way that the SHW system contributes optimally to energy savings.

Pipe lengths should be minimized to avoid thermal capacitance and heat loss. Design shall accommodate thermal expansion and contraction of all pipes and the fluid within the pipes.

All plumbing components shall be copper or compatible materials and all exterior hardware shall be resistant to corrosion (stainless steel, anodized aluminum, fiberglass, PVC).

Include with each system components that consist of a solar collector array, array support structure, storage tank, interconnecting piping and fittings, and as required by the system type, any necessary pumps, controls or heat exchangers, as well as all other accessories and equipment required for the proper operation of the solar system.

Performance Requirements

Solar water heating systems must be safe, reliable, require no operator intervention for normal operation, be visually unobtrusive, and be designed and installed in accordance with all applicable codes. Design and size the system so that solar energy supplies approximately the percent of the annualized hot water demand ("Required Solar Fraction") specified:

Daily hot water demand: M_{load} = <enter your hot water use here, for example 2,700 kg (720 gallons)>
Incoming cold water temperature: T_{mains} = <enter your cold water temperature here, 20C (68F) for example>
Hot water delivery temperature: T_{del} = <enter your value here, 60C (140F) for example>
Required solar fraction: at least SF = <enter your value, 75 percent for example>

Any additional information regarding daily demand calculations, patterns of weekly or monthly variations in the load or descriptions of end uses of the hot water shall be ascertained by the contractor or estimated. The solar water heating system shall be designed to fit within the available exposed roof area as listed in the following table.

Roof Portion	Length, m (ft)	Width, m (ft)	Roof Orientation, (180 = South)	Roof Pitch Angle (90 = vertical)
Roof area-1				
Roof area-2				
Other roof areas available…				

System size and design parameters shall be determined based on minimizing life cycle cost for the building owner. System shall be designed to save as much conventional energy as possible, but within the economic limits of diminishing returns due to over-capacity and low system efficiency.

Submittals

Submit the following information. Submittals shall be in accordance with the project schedule and be submitted 6 copies in both electronic and hardcopy form.

Schedule: Contractor shall submit schedule showing when each portion of the project will be completed. Schedule shall detail the hours of work, access to locations, delivery and laydown of materials, requirements for staging areas and timing and area requirements of crane or other equipment. Coordinate schedule with building management.

Product data: Submit commercial products data with performance charts and curves; annotate descriptive data to show the specific model, type, dimensions and weight of each item. Contractor shall submit the manufacturer's product specification sheet and the manufacturer's installation instructions for all materials to be used. Product literature must be current and representative of the materials used.

Solar system design narrative: Submit calculations of solar system performance leading to the proposed design. Submit reports resulting from the use of any design or performance simulation software used in the design. Submit collector array structural design information sealed by a professional engineer. Describe the number of solar collectors, piping arrangement, type and ratings of pumps, tanks, and all other components, roof penetration and mounting details. Report the temperature and flow rate details, confirming that temperature and velocity limits are observed. Submit roof structural loading details confirming that loading does not exceed roof framing capacity.

Specifications: Submit a full set of specifications that express all information required for a contractor to build the system in sufficient detail for approval and direction of the construction work. Specifications shall include installation and interconnection information and performance and quality characteristics.

Drawings: Provide drawings for each discipline (plumbing, electrical, roofing, structural). Provide separate drawings for demolition and new work and drawings of details such structural attachment and roof flashing details. Each drawing shall be clearly labeled and include project title, designer name and contact information, drawing number and key plan. Set of drawings shall include cover sheet with list of drawings. Drawings shall be stamped with name, certificate number, and seal of engineer licensed to practice within the jurisdiction. Drawing shall include: system schematic diagram; a collector layout and roof plan (or ground lay-out) noting reverse-return piping for the collector array; waterproofing roof details; a system plumbing riser diagram; a list of operation and installation instructions; and a list of design information including collector length and width, recommended collector flow rate and pressure drop at that flow rate, number of collectors, number of collectors to be grouped per bank, gross area and net aperture area of collectors, collector fluid volume, collector filled weight, weight of support structure, and tilt angle of collectors from horizontal. Include in the drawings, complete wiring and schematic diagrams, proposed pipe pitch and any other details required to demonstrate that the system has been coordinated and will properly function. Show proposed layout and anchorage of equipment and appurtenances, and equipment relationship to other parts of the work, including clearances for maintenance and operation. Provide a detail of the joint connection between the solar collector mounting brackets and the roof membrane.

Instructions: Submit diagrams, instructions, and other sheets, including a system schematic, wiring and control diagrams, and a complete layout of the entire system for each system type to be installed. Include with the instructions, in typed form, condensed operating instructions explaining preventive maintenance procedures, methods of checking the system for normal safe operation and procedures for safely starting and stopping the system, methods of balancing and testing flow in the system, and methods of testing for control failure and proper system operation. Instruction submittal shall be mounted with clear plastic cover suitable for mounting near the equipment and also in hardcopy form for filing in the building office.

Operating and maintenance manuals: Submit manuals that detail the step-by-step procedures required for system filling, startup, operation, and shutdown. Include in the manuals the manufacturer's name, model number, service manual, parts list, and brief descriptions of all equipment and their basic operating features. List routine maintenance procedures, possible breakdowns and repairs, recommended spare parts, troubleshooting guide, piping and equipment layout, balanced fluid flow rates, and simplified wiring and control diagrams of the system as installed.

Field test reports: Submit reports of piping hydraulic pressure test, water potability test, system performance test.

(continued)

Shop drawings: Contractor shall submit, prior to fabrication, shop drawings showing system design, all major components, sequence of operation, all products specified, erection procedures and accessories required. Drawings shall show details of structural attachments; details of flashing components and other accessories such as details of fastening and anchorage methods of materials and framing. Electronic versions of all drawing submittals shall be included.

Samples: Contractor shall submit, prior to fabrication, samples of exposed materials in the paint color specified, for architectural selection and/or approval.

Warranties: Contractor shall submit all warranty information and certificates for each component warranted by the manufacturer.

Quality control plan: Submit description of plans to ensure quality. Include specific tests to be conducted.

Safety plan: Submit description of plans to ensure safety on the worksite.

As-built drawings: Showing details as actually installed.

Quality Assurance

Installer qualifications: A qualified contractor (and subcontractors), licensed as appropriate, and familiar with solar collector and mechanical/electrical component installation, shall install the solar water heating system and parts described herein. The system shall be designed by a company experienced with solar water heating technology with a minimum of five (5) years history designing and installing successful projects. Manufacturers of mechanical/electrical components shall be ISO 9001 compliant.

A quality control plan is required to keep track of all quality control measures and tests.

Delivery and Storage

Protect materials during transport with suitable packaging and handling. Inspect all materials upon delivery. Do not deliver materials until provision for on-site storage and protection are available. Materials shall be delivered to the site in a dry and undamaged condition and unloaded per the manufacturer's instructions. The installer shall inspect materials for damage upon arrival to the site. Materials shall be stored out of contact with the ground in weather-tight coverings to keep them dry per the manufacturer's recommendations. Install covers at a slight slope so that any water may drain off the surface. Do not stack other materials or work on top of the stored solar collectors.

Part 2: Products

General Equipment Requirements

Standard or preapproved products: Furnish materials and equipment that are the standard products of a manufacturer regularly engaged in the manufacture of such products and which essentially duplicate items that have been in satisfactory use for at least 1 year prior.

Nameplates: Provide each piece of major equipment with the manufacturer's name, address, type or style, model or serial number, and catalog number on a plate.

Piping system

Provide a piping system complete with pipe, pipe fittings, valves, strainers, expansion loops, pipe hangers, inserts, supports, anchors, guides, sleeves, and accessories with this specification and the drawings. Pipe shall be designed to observe limits on flow velocity, pressure drop, and gauge pressure associated with the pipe type and characteristics.

Provide, install and test the piping. Provide piping flow rates below 5 feet per second. Piping shall be Type L or Type M copper tubing, ASTM B-88, with 95-5 tin-antimony soldered joints. Plastic pipe will be considered if documentation confirms it is suitable for the application and approved by building management/owner. If cold water piping supplying the SWH system is of another type, such as PVC, it shall be replaced within 10 feet of the SWH system with copper to avoid bulging and rupture due to proximity to the higher temperatures of the solar system.

Pipe insulation: Furnish pipe insulation and coverings. Insulation shall be rated for the maximum temperatures to be expected in that portion of the system. Provide outside array piping insulation with a capability of withstanding 250 degrees F, except that piping insulation within 1.5 feet of collector connections shall be capable of withstanding 400 degrees F. Protect outside piping insulation from water damage and ultraviolet degradation with a suitable outer coating manufactured for this purpose (aluminum, sunlight resistant PVC or approved equal).

Calibrating balancing valves (for multiple collector banks): If systems are proposed with multiple collector banks, provide at each bank a calibrated balancing valve suitable for system pressure and temperature. Furnish calibrated balancing valves with bronze body/brass ball construction with seat rings compatible with system fluid and differential readout ports across valve seat area. Provide readout ports fitted with internal insert of compatible material and check valve. Provide calibrated balancing valves with a memory stop feature to allow valve to be closed for service and reopened to set point.

Pressure gauges: Provide pressure gauges with throttling type needle valve or a pulsation dampener and shutoff valve. Furnish a 3 1/2-inch minimum dial size.

Thermometers: Supply thermometers with wells and separable bronze sockets.

Pipe hangers and supports: Support and hang piping so that the weight of the piping is not supported by drywall, siding, or other building members not designed to bear load. Support piping so that thermal expansion and contraction of pipe lengths is accommodated.

Valves: Provide valves compatible with the piping. Ball valves shall be used for shutoff, with full port, bronze body, bronze ball, and Teflon seat. Bronze hose-end gate valves shall be used for draining system and shall be installed at low points of piping.

Labels: Labels shall be visible on collector supply and return and potable water supply and return pipes. Warning labels shall be posted on or near system components warning of any hazards such as high temperatures, high pressures, or the potential for discharge of fluid such as pressure relief valve discharge.

Collector Subsystem

Solar collector construction: The type of solar collector proposed shall be compatible with the proposed system type. Collectors shall be selected based on optimal cost and performance. Depending on the temperature requirements of the system, collector may be unglazed (low temperature), single or double glazed (midtemperature), or evacuated-tube (high temperature) with selective or painted absorber surfaces. Furnish collectors of weather-tight construction and with an aluminum casing. Provide aluminum or stainless steel mounting brackets and hinges. Furnish stainless steel assembly hardware including all bolts, washers, and nuts. Install collectors such that tubes on the absorber plate drain by gravity. Provide cover glazing completely replaceable from the front of the collector without disturbing the piping or adjacent collectors.

Collector warranty: Provide a minimum 10-year warranty against the following: failure of manifold or riser tubing, joints or fittings; degradation of absorber plate selective surface; rusting or discoloration of collector hardware; and embrittlement of header manifold seals. Include with the warranty full repair or replacement of defective materials or equipment.

Solar collector performance: Plot thermal performance on the thermal efficiency curve in accordance with ASHRAE 93 showing the product of glazing transmittance and plate absorptivity and also the thermal loss coefficient, W/C (btu/hr/F) of the solar collector. Show manufacturer's recommended volumetric flow rate and the design pressure drop at the recommended flow rate. Indicate the manufacturer's recommendations for the number of collectors to be joined per bank while providing for balanced flow and for thermal expansion considerations.

Solar Collector Array

Net absorber area and array layout: collector array shall be oriented so that all collectors face the same direction. Space collectors arranged in multiple rows so that no shading from other collectors is evident between 1000 hours and 1400 hours solar time on the winter solstice. Collectors should be south facing and a tilt equal to the local latitude, but other orientations may be considered for approval. Indicate minimum spacing between rows.

Piping: Connect interconnecting array piping between solar collectors, in a reverse-return configuration with approximately equal pipe length for any possible flow path. Indicate flow rate through the collector array. Provide each collector bank isolated by valves, with a pressure relief valve and with the capability of being drained. Locate manually operated air vents at system high points, and pitch array piping a minimum of 2 cm/m (0.25 inch per foot) so that piping can be drained by gravity. Do not install low points in the piping from which fluid may not be drained. Supply calibrated balancing valves at the outlet of each collector bank as indicated.

Supports for solar collector array: Provide support structure for the collector array of aluminum, stainless steel, or other corrosion-resistant approved material. Furnish a support structure which secures the collector array at the proper tilt angle with respect to horizontal and orientation with respect to true south. Consideration should be made to mounting collectors parallel to the pitched roofs. The collector tilt angle may vary by +/–25 degrees, and the azimuthal angle may vary by +/–45 percent from the optimal tilt and azimuth. Provide a support structure that will withstand the static weight of filled collectors and piping, wind, seismic, and other anticipated loads without damage. For heavy systems, such as integral storage collectors, provide structural reinforcement for the roof across at least four rafters and provide verification that the structural modifications proposed are satisfactory. Provide a support structure which allows access to all equipment for maintenance, repair, and replacement. Neoprene or EPDM washers shall separate all dissimilar metals. Depending on system type, supports for solar array could terminate in ballast blocks to avoid roof penetrations.

Solar Preheat Storage Tank

Provide a thermal energy storage solar preheat tank with a storage capacity of at least 60 l/m^2 (1.5 $gallons/ft^2$) of collector area. Insulate each tank with fiberglass or foam with a loss coefficient of not more than 0.5 W/m^2C. Protect the insulation by a PVC or steel jacket. Provide a tank rated at for the maximum pressure and temperature to be encountered in system operation, including long periods of solar heat gain without hot water removal. Provide the interior of tank with glass lining or lining suitable for potable hot water service. Materials used in the storage tank must be resistant to corrosion themselves and must not cause corrosion of other system components (through galvanic action of dis-similar metals). Provide the water tank with a drip tray with drain line discharging to a floor drain or other suitable place to drain the water from the tank.

Transport Subsystem

Heat exchanger (if required by system design): For system designs requiring a heat exchanger, provide a minimum design pressure rating compatible with the maximum system pressure. Construct heat exchanger of corrosion resistant materiasls (316 stainless steel, titanium, copper-nickel, brass, or approved equivalent). Furnish heat exchanger with a capability of withstanding the maximum expected temperature of the system. In general, double-wall heat exchangers are required by code for use with potable water systems.

(continued)

Pumps (for active systems): For active solar system designs requiring a pump, provide electrically-driven, single-stage, centrifugal type circulating pumps manufactured for the purpose. Support pumps on a concrete foundation or mounting intended for the purpose, or by the piping on which installed if appropriate to the size. Construct the pump shaft of corrosion resistant material with a mechanical seal. Provide corrosion resistant impellers (e.g., stainless steel) and casings (e.g., bronze). Control motors with switches that can be activated by either the differential temperature controller or by manual override (hand-off-automatic). Provide pumps complete with motor, and any other accessories to operate the pump. Pumps shall be installed with isolation valves so the pump can be serviced without draining the system.

Heat-transfer fluid: Heat-transfer fluid shall be compatible with all materials in the system. The nature and amount of heat-transfer fluid will depend on the type of system proposed and the freeze conditions encountered at the site. Any antifreeze, conditioners or corrosion inhibitors added to the heat-transfer fluid must be nontoxic and intended for use in potable water systems.

Control and Instrumentation Subsystem

Differential temperature control equipment (if required): If the system design includes active controls, furnish the differential temperature control equipment as a system from a single manufacturer. Furnish a solid-state electronic type controller complete with an integral transformer to supply low voltage. Controller accuracy shall be plus or minus 1/2 degree C (one degree F). Supply controllers that are compatible with the supplied temperature sensors. Provide differential controls with display of operating mode and status and display of temperature readings of all temperatures sensed. Supply controls with a visual indicator when pumps are energized. Provide a controller that will identify open and short circuits on both the solar collector temperature sensor circuit and the storage tank sensor circuit.

Temperature sensors (if required): Provide temperature sensors that are compatible with the differential temperature controller, with an accuracy of plus or minus 1 percent at 77 degrees F. Supply sensors that have passed an accelerated life test conducted by subjecting thermistor assemblies to a constant temperature of 400 degrees F or greater for a period of 1,000 hours minimum with an accuracy of within plus or minus 1 percent as stated above. Furnish hermetically sealed sensors. Provide immersion wells or watertight threaded fittings for temperature sensors. Temperature sensors shall be mechanically attached to the surface they are measuring and wire to the sensor must be mechanically attached and protected along its length.

Tempering valve (very important): All systems installed under this procurement action ***must*** have a tempering or mixing valve to limit the temperature of the hot water supplied to the plumbing fixtures. The tempering valve is to be located downstream of the electric water heater and is to be set to a temperature suitable for the application.

Electrical Work

If pumps are required in the system design, provide electric motor-driven equipment complete with motor, motor starters, and controls. Motors shall be sized to drive the pump at the specified capacity without exceeding the nameplate rating of the motor. Provide electrical equipment and wiring in accordance with NFPA 70. Furnish motor starters complete with thermal overload protection and other appurtenances necessary for the motor control specified. Provide each motor of sufficient size to drive the equipment at the specified capacity without exceeding the nameplate rating of the motor.

Structural Framing

Provide structural reinforcement, framing, subframing, and anchors as a complete system capable of permanently meeting all structural requirements.

Fabrication

Components shall be fabricated to the greatest extent possible in the factory ready for field assembly.

Part 3: Execution

Inspection

Examine the building to verify that the structure is ready for panel installation. Move any objects on or in front of the area where solar panels are to be mounted. All roof attachments and structural supports shall be in place and connections shall be tightened before installation of the solar collectors proceeds. Prior to ordering materials, field-check dimensions to confirm plans and check alignment of structural supports.

If any condition is found which will prevent proper execution of his work, the installer shall report such condition in writing to the building project manager and shall not proceed until unsatisfactory conditions are corrected. Beginning the installation means the Contractor has accepted the existing conditions.

Coordination

The contractor shall coordinate the installation of the solar water heating system with the building operation schedule. The Contractor shall coordinate with the contracting officer on the locations and appearance of all exposed equipment, including but not limited to the solar collectors, piping, pumps, heat exchanger, tanks, and control equipment.

The contractor shall coordinate installation of the solar collectors and other components for compliance with performance requirements and to achieve proper ongoing operation of the system.

Contractor shall coordinate with roofing contractor holding the warranty for the existing work to review designed roof attachments and service the roof following construction of the solar water heating system. Construction of the solar water heating system shall not void roof warranty.

Installation

Contractor shall perform all construction necessary for the installation of the system based on the design. Schedule for installation and work hours shall be established in the contract schedule. Work hours and areas of the building available to the contractor shall be coordinated with building management. Tools and materials may not be left on site unsecured.

Install piping straight and true to bear evenly on hangers and supports. Do not hang piping from drywall or suspended ceilings. Keep interior and ends of new piping thoroughly cleaned of foreign matter. Keep piping systems clean during installation by means of caps on the ends. Discharge storage tank pressure and temperature relief valves into floor drains. Horizontal runs should be flat and vertical runs should be plumb. Install any multiple pipes in an order which does not require them to cross or interfere with each other or other building systems. Provide air vents with threaded plugs or caps. Install control and sensor wiring so that it is protected in conduit, raceway, or protected within walls.

System flushing and disinfection: Flush and disinfect the piping system.

Penetrations: Any penetrations through walls, ceilings, or other parts of the building shall be booted, sealed, or returned to original appearance. All roof penetrations shall be made permanently waterproof. Copper or other approved flashing shall be used. Contractor shall provide a five-year warranty on materials and labor for any roof leaks due to or arising out of the solar water heating system installation.

Array support: Install array support in accordance with the recommendations of the collector manufacturer.

Pipe expansion: Provide for the expansion and contraction of supply and return piping with changes in the direction of the run of pipe or by expansion loops. Do not use expansion joints in the system piping.

Valves: Install ball valves at the inlet and outlet of each bank of manifolded collectors. Install calibrated balancing valves at the outlet of each collector bank and mark final settings on each valve. Balance flow through the collector piping with at least one balancing valve left in the full-open position. Locate tempering mixing valve downstream of auxiliary water heater to control hot water delivery temperature.

Inspection, Testing, and Commissioning

Instructions: Post the framed instructions (as described above) before acceptance testing of each system.

Acceptance testing and final inspection: Maintain a written record of the results of all acceptance tests, to be submitted in booklet form. Provide the following tests:

Hydrostatic test: Hydrostatically test each system to the maximum possible system pressure. Isolate any instrumentation not suitable for the intended test pressure.

Operational test: Operationally test each system over a period of 48 consecutive hours with sufficient solar insolation to cause activation of the solar energy system during daylight hours. Test for balanced flow between arrays with noninvasive flow meter or by measuring the outlet temperature of each bank of collectors. Demonstrate that the pump will start after the collectors have been warmed by the sun and will stop during cloudy weather or in the evening. Performance parameters recorded during the operational test include: insolation in the plane of the array, ambient temperature, temperature of cold water entering the system, temperature of solar preheated water exiting the system, flow rate of fluid through each bank of the collector array (or estimate based flow of total array and temperature outlet of each bank), replace thermistors with potentiometers and check function of controller to start/stop pumps and overheat protection by changing the resistance of the potentiometer, test of heat-transfer fluid freeze point and pH, and other tests required by the commissioning authority. Confirm that all valves and controls are left in the permanent operating position.

Water potability test: confirm through laboratory testing that the potable water delivered by the system is free of contaminants and suitable for human consumption. Meet or exceed drinking water standards set by the authority having jurisdiction.

Temperature sensor diagnostics: As required by system design, demonstrate the controller will correctly identify open and short circuits on both the solar collector temperature sensor circuit and the storage tank sensor circuit.

Documentation: Results of inspections and tests shall be recorded in a written record as required in the quality control plan. Results shall include item tested, location, date, test parameters, measured raw data, state of construction completion, operating mode, names and contacts of persons performing the tests and witnesses, test equipment description, and conclusions.

Field Training

Provide a field training course for operating and maintenance staff after the system is functionally complete. Include in the training a discussion of the system design and layout and demonstrate routine operation, maintenance and troubleshooting procedures. Cover operational indicators, modes of operation, control status indicators, periodic planned maintenance, troubleshooting and repair, system startup and shutdown/bypass, removal and replacement of parts. Written training materials are to be provided and training is to be recorded on video for viewing by new maintenance staff.

Warranty

Entire system as a whole shall carry one-year warranty, signed by a principal of the contracting firm, including parts and labor. Warranties, guarantees, final certifications, and similar documents associated with individual components are to be transferred to the name of the building owner upon completion of the project.

Cleaning

Leave all areas affected by the work clean and orderly and remove any unused materials or scraps.

REFERENCES

ANSI. 2004. ANSI/ASME Pipe Schedule B26.10M. American National Standards Institute/American Society of Mechanical Engineers. http://webstore.ansi.org/RecordDetail.aspx?sku=ASME%20B36.10M-2004&source=google&adgroup=asme&gclid=CM3igI3kwrYCFaNhMgodikIAKA

Aquatherms. 2009. "About Aquatherm." Aquatherm Industies, Inc. http://warmwater.com/about-aquatherm-solar-pool-heating/. (accessed March 6, 2012).

ASHRAE. 1977. *Methods of Testing to Determine the Thermal Performance of Solar Collectors.* Atlanta, GA: American Society of Heating Refrigeration and Air Conditioning Engineers.

———. 1988. *Active Solar Water Heating System Design Manual.* Atlanta, GA: American Society of Heating Refrigeration and Air Conditioning Engineers.

———. 1990. *Guide for Preparing Active Solar Heating System Operation and Maintenance Manuals.* Atlanta, GA: American Society of Heating Refrigeration and Air Conditioning Engineers.

———. 1991. *Active Solar Heating System Installation Manual.* Atlanta, GA: American Society of Heating Refrigeration and Air Conditioning Engineers.

Beckman, W., and J. Duffie. 2006. *Solar Engineering of Thermal Processes.* 3rd ed. New York: John Wiley and Sons.

Both, A. J. 2007. Greenhouse Glazing. Energy. hrt.msu.edu/Energy/Notebook/pdf/Sec1/AJ_Both_Greenhouse_Glazing.pdf. (accessed June 2, 2012).

Burch, J., and P. Erickson. 2004. "Using Ratings Data to Derive Simulation Model Inputs for Storage Tank Water Heaters." 393–99. Proceedings of the Solar 2004 Conference. Boulder, CO: American Solar Energy Society

Butti, K., J. Perlin 1980. *Golden Thread: 2500 Years of Solar Architecture and Technology*. 3rd ed. Palo Alto, CA: Cheshire Books.

Christensen, C., G. Barker 1998. "Annual System Efficiency of Solar Water Heating Systems." 291–96. Proceedings of American Solar Energy Society Conference. Boulder, CO: American Solar Energy Society.

DOE BTP. 2011. "Buildings Energy Data Book." EERE Buidling Technologies Program. buildingsdatabook.eren.doe.gov/TableView.aspx?table=3.1.13 (accessed March 2, 2012).

DOE OBT. 2011. "Building Energy Software Tools Directory." Office of Building Technologies http://apps1.eere.energy.gov/buildings/tools_directory/ (accessed March 16, 2012).

FAFCO. 2010. "FAFCO Solar Water Heating." FAFCO Product Literature. www.fafco.com/files/Solar%20Bear%20Panel%20Spec%2006963C.pdf (accessed March 6, 2012).

FEMP. 1995. *Residential Heat Pump Water Heaters.* Washington DC: Federal Energy Management Program.

FSEC. 2007. "Solar Thermal Collector Certification." Florida Solar Energy Center. www.fsec.ucf.edu/en/certification-testing/STcollectors/standards/index.htm (accessed February 11, 2012).

He, T., Zheng, R., and L. Zhang. 2011. *Introduction to Standards and Testing. Domestic Use of Energy.* Cape Town, South Africa: Cape Peninsula University of Technology.

Hendron, R. and Engebrecht, C. 2009. Building America Research Benchmark Definition. National Renewable Energy Laboratory Golden CO. Technical Report NREL/TP-550-47246. http://www.nrel.gov/docs/fy10osti/47246.pdf January 2010

Hottel, H. A. and Woertz B. 1942. "Performance of Flat Plate Solar Collectors." *Transactions of the ASME.* no volume number 64–91.

IEA. 2009. "Renewable Energy Essentials: Solar Heating and Cooling." [http://www.iea.org/publications/freepublications/publication/Solar_heating_cooling.pdf (OECD/IEA, Producer):

Incropera, F., and D. DeWitt. 2005. *Fundamentals of Heat and Mass Transfer.* 7th ed. New York: John Wiley and Sons.

Kennedy, C. 2002. *Review of Mid- to High-Temperature Solar Selective Absorber Materials.* National Renewable Energy Laboratory. Golden, CO: National Renewable Energy Laboratory.

May, K., G. Barker, E. Hancock, A. Walker, R. Westby, and J. Dominick. 2000. "Performance of a Large Parabolic Trough Solar Water Heating System at Phoenix Federal Correctional Institution." *Journal of Solar Energy Engineering* 122: 165–69.

Minister of Natural Resources Canada. 2012. "RETScreen International." (January 16). www.retscreen.net (accessed August 19, 2012).

NABCEP. (2011, 9 29). *Solar Thermal Installer Certification.* (September 29) North American Board of Certified Energy Practitioners. www.nabcep.org/certification/solar-thermal-installer-certification (accessed February 11, 2012).

NASA LARC. 2012. "Surface Meteorology and Solar Energy." NASA.gov. eosweb.larc.nasa.gov/sse/PCM Products Inc. 2011. Phase Change Materials Thermal Energy Storage. See www.pcmproducts.net/files/design_manual.pdf; table of properties on page 17.

RS Means. 2011a. *Mechanical Cost Data.* 34th ed. Norwell, MA: RS Means and Co.

———. 2011b. *Green Building: Project Planning and Cost Estimating.* Kingston, MA: RS Means and Co.

Smith, C., and T. Weiss. 1977. "Design Application of the Hottel-Whillier-Bliss Equation." *Solar Energy* 19 (2): 109–113.

Solar Mirror. 2012. "Solar Mirror." Absorptivity and Emissivity of Common Materials and Coatings. www.solarmirror.com/fom/fom-serve/cache/43.html. (accessed June 2, 2012).

SRCC. 2012. "Solar Rating and Certification Corporation." OG-100 Ratings. solar-rating.org (accessed June 20, 2012).

Walker, A. 2009. "An Heuristic Approach to Renewable Energy Optimization." Energy Sustainability 2009. San Francisco: American Society of Mechanical Engineers.

Walker, A., C. Christensen, and G. Yanagi. 2003. Time-of-Use Monitoring of US Coast Guard Residential Water Heaters with and without Solar Water Heating in Honolulu HI. ASME International Solar Enegy Conference. Kohala, HI: American Society of Mechanical Engineers.

Walker, A., and Dominick, J. 2000. Performance Contracting for a Solar Water Heating System at Phoenix Federal Correctional Institution. AIAA. Las Vegas: American Institute of Aeronautics and Astronautics.

Walker, A., C. Kutscher, A. Halvorsen,C. McKenna, D. Chambers, and K. 2006. "Design and Analysis of a Large Solar Industrial Heat Plant for Frito Lay in Modesto, CA." ES2007 Energy Sustainability Conference, Long Beach, CA. New York: American Society of Mechanical Engineers.

Walker, A., F. Mahjouri,, and B. Stiteler. 2004. Evacuated Tube Heat Pipe Solar Collectors Applied to the Recirculation Loop of a Federal Building (SSA Philadelphia). National Solar Energy Conference. Portland, OR. Boulder, CO: American Solar Energy Society.

Walker, A., and Roper, M. 1992a. "Implementation of the NREL SDHW Short-term Monitoring Method." Solar 92: The National Solar Energy Conference 21st ASES Annual Conference. Cocoa Beach, FL. Boulder, CO: American Solar Energy Society.

———1992b. "Technical Inspection of 185 Active Solar Heating Systems in Colorado." Solar 92: The National Solar Energy Conference, 21at ASES Annual Conference. Cocoa Beach, FL. Boulder, CO: American Solar Energy Society.

Winn, B., S. Karaki, G. Lof, G. Johnson, D. Ward, W. Duff et al. 1980. *Solar Heating and Cooling of Residential Buildings Design of Systems*. Fort Collins, CO: Colorado State University. Published by Superintendent of Documents, US Government Printing Office, Washington DC.

Wong, P. 2011. "Solar Thermal Collector Manufacturing Activities 2009." US Energy Information Administration (EIA), (accessed December 26, 2011) www.eia.gov/renewable/annual/solar_thermal/.

5

Solar Ventilation Air Preheating

Preheating of ventilation air with a transpired solar collector offers one of the most cost-effective applications of solar heating. A transpired solar collector is made from metal siding which is painted a dark color and perforated with tiny holes. Solar heat is added to the ventilation air as it is drawn through the holes by the action of a fan. Due to simplicity and minimal hardware, the cost of this product is low. Yet the efficiency is very high due to low-temperature operation and due to its innovative design based on a principle called the "thermal boundary layer." Its application is limited to preheating of ventilation air, drying operations, and other processes that require heating of ambient air.

John Hollick of Conserval Engineering invented the transpired solar collector for preheating ventilation air and introduced it with the name "SolarWall" in 1994. He began manufacturing transpired collectors in Buffalo, New York. At about the same time, Craig Christensen, Chuck Kutscher, Keith Gawlik, and Greg Barker at the Solar Energy Research Institute (SERI, now NREL) were characterizing the science. Their work established useful relationships for heat transfer and pressure drop for a transpired collector. Parameters important to solar ventilation air preheating system design and performance include the wall area, the solar absorptivity of the paint, the air flow rate, and the porosity of the wall (hole spacing). Careful monitoring of one of the first installations of the technology, a 30 m^2 (320 ft^2) transpired collector for preheating 1.4 m^3/s (3,000 CFM) of ventilation air on a chemical storage building at the Solar Energy Research Institute and installed in 1990, demonstrated the efficacy of the technology and reported a savings of 14,310 kWh/year and an annual-average efficiency of 63 percent. More recently, Saeed Moaveni of Norwich University, Patrick Tebbe, Louis Schwartzkopf, Joseph Dobmeier, and Joseph Gehrke of Minnesota State University, and Matthew Simones at University of Missouri (Moaveni 2011) have reported on modeling which includes the mass of the supporting wall, and Barker and Kiatreungwatana (Barker and Kiatreungwattana 2011) have drawn some design recommendations from careful monitoring studies.

By 2009, over 1,500 systems had been installed with a combined collector area of over 300,000 m^2 (3 million ft^2). Much of this has been on industrial facilities in the northeastern US, Canada, and Europe. The technology has application on any building that has a steady requirement to heat ventilation air. Buildings in warm climates or buildings that have a lot of internal heat gain (from computers, etc.) are not candidates. Solar Ventilation Air Preheating reduces the savings associated with exhaust-air heat recovery, although the two may be used together.

In a "product of the week" posting titled "Transpired Solar Collector Performance: More Than Hot Air," at BuildingGreen.com, products editor Brent Ehrlich mentions Conserval Engineering's SolarWall and licensee ATAS International's Inspire but also talks about two others: Matrix Energy's MatrixAirTR and Enerconcept Technologies' Lubi System (Ehrlich, 2011). All of them are perforated metal except the Lubi System, which has a polycarbonate absorber and a transparent cover. CSA International Certified Products Listing of unglazed transpired solar collector products includes: Conserval Engineering Inc's. Solarwall (www.solarwall.com); Matrix Energy Inc.'s MatrixAir™ (www.matrixenergy.ca); Enerconcept Technologies Inc.'s Unitair; Luba Solar (www.enerconcept.com/en/solar-air-heating-products/lubi/); and VTP's Murox (www.murox.ws) (CSA International 2011).

The technology has also been used in other applications such as to dry crops at installations in California and Latin America and to heat combustion air in Europe, and it may have application whenever heating of ambient (outdoor) air is required. There is no way to circulate air back to the inlet of an unglazed transpired collector. However, some glazed solar collectors have been manufactured with transpired absorber plates inside of them to reduce heat loss off the glass, and these may be used to reheat air circulated within a solar energy system.

Interview with John Hollick

John Hollick, (see figure 5-1), is president of Conserval Engineering Inc. of Toronto, SolarWall Europe Sarl of Paris, and Conserval Systems of Buffalo, New York, which manufacture the SolarWall solar air heating system, incorporating the transpired solar collector. Hollick invented the unglazed transpired collector (branded SolarWall®), which set a standard for solar air heating because of its high efficiency and low cost. He is a registered Professional Engineer. He began designing solar air heating systems and formed Conserval in 1977. In the 1990s he patented and introduced the all-metal building integrated solar wall heating system, and has gone on to see the installation of over 2,000 systems in 30 countries. Hollick has been granted several patents related to the SolarWall transpired collector, including his latest application to remove heat from PV modules by mounting them onto SolarWall panels and methods to cool ventilation air using nocturnal radiation cooling. He is a firm believer in using the same roof space for both solar electric and solar heating/cooling solutions. Currently, he is working with the governments of several countries to establish worldwide standards for solar air heating.

Figure 5-1. John Hollick with a freestanding version of the transpired solar collector that he invented. (Photo courtesy of Conserval Engineering).

To what do you attribute the success of the transpired collector?

People believed in the product starting with our family and dedicated staff and extending to the US Department of Energy, Natural Resources Canada, and Fortune 500 Clients. The goal was to have a solar heating system that was cost-effective and not dependent on grants or tax credits. In the 1980s we started providing solar heat for factories with large walls and learned that we could eliminate a lot of materials by using the south wall as the support structure. Further development led to the elimination of the glazing and using only a single perforated metal sheet which further lowered costs. It still took another decade to gain market acceptance and the climate change issue has certainly been a major factor recently.

For years you were the only supplier of the transpired solar collector, now there are competitors. Are there differences between the products on the market?

Performance testing is vital to allow specifiers to compare product offerings. Anyone entering this market should also have engineers on staff to design the complete system so it integrates the solar heat collected on the building with the HVAC system and controls. SolarWall is building-integrated and as such requires design expertise to ensure that solar heated air passes through each and every of the thousands of holes on a typical installation and then into the building's ventilation system. The installation should also be architecturally attractive.

Are there innovative developments coming or is this technology fully mature in your opinion?

There are a number of new innovative developments—the PV thermal system is very exciting as the SolarWall system acts as a heat sink for the PV modules, and since PV/T is solar cogeneration, it maximizes the solar energy (heat and power) output from a given surface.

In our new two-stage SolarWall, the air is heated twice, which is ideal for obtaining higher temperatures typical of space heating applications or for heating water through a heat exchanger.

Probably the most interesting new concept is the ability to cool air below ambient temperature. Nocturnal radiation cooling occurs on clear nights, and roof mounted transpired collectors can utilize this phenomena to lower air temperature as much as 5 C (10 degrees F) below ambient from sunset to sunrise. Now we have a solar heating and cooling system that can work 12 months a year.

The next big development will be in heat storage and we are currently investigating options in this area.

What do you think is important regarding codes and standards related to solar ventilation air preheating?

Current codes deal with saving energy and not producing it. We still need to produce energy, especially for heating fresh air, as there is only so much that can be conserved. Codes that include renewable on-site energy production are the next logical progression in building codes. Parts of Europe are or will soon require new buildings to incorporate some percentage of on-site renewable energy. A requirement for at least 20 percent on-site energy (heat and electricity) generation is doable and likely to start appearing in some jurisdictions in USA and Canada beginning with large buildings. Codes should address the building integrated aspects of using the walls or roof as the heater, connecting them to the ventilation systems and control strategies.

Codes and solar test standards are important. Even as Europeans set requirements for use of renewable energy in buildings, a lack of a test standard for air collectors in Europe has limited use of solar air heaters on that continent. Current solar test standards were designed for factory-built solar panels and not for building-integrated site built designs. New test standards are required to ensure that designs perform as expected. A new international test standard for solar air heating systems involving the US, Canada and Europe is currently being developed as part of an International Energy Agency Task 43 initiative, and many of the new test procedures that we pioneered for testing the transpired collector are to be included in this new standard.

What has been your experience with clients who have installed transpired solar collectors?

Clients are amazed at the amount of free heat that a typical system produces, and many have also noticed an improvement in the indoor air quality. Since the heat is free, a building operator can increase the ventilation rate and the indoor temperature and still save energy while improving the comfort level. Maintenance personnel like the fact that the transpired collector has no maintenance. The building integrated feature of a SolarWall system is interesting as it does not look like a traditional solar panel. Most clients like the fact that their architect has integrated the solar heater to blend in with the building fabric but a few clients want their solar heater to stand out and have even painted SolarWall on their panels to indicate solar heating on their building.

OPERATING PRINCIPLE OF THE TRANSPIRED AIR-HEATING SOLAR COLLECTOR

Boundary-layer Theory

Consider an up-close view of the surface of a transpired solar collector mounted on a building as shown in Figure 5-2. Even if wind blows by at a high speed, the air that is in contact with the metal collector surface is not moving because the surface is not moving. This is known as the "*law of the wall*" in fluid mechanics. Within a layer of air about 1.0 mm thick next to the surface, known as the *velocity boundary layer*, the velocity transitions from zero at the surface to whatever the ambient wind speed is outside of the boundary layer. The boundary layer thickens as the wind moves along the plate away from the leading edge, but by drawing air in through tiny holes in the wall, the boundary layer reaches a maximum thickness and then stays that thickness for the rest of the distance along the wall.

Similarly, within a thin "thermal boundary layer" the temperature transitions from the surface temperature to the ambient temperature as shown in the conceptual diagram of Figure 5-3. Since air has a low viscosity and low thermal conductivity, the thermal boundary layer is thicker than the velocity boundary layer, but they are both about the same thickness—about the thickness of a coin.

Within the velocity boundary layer, the air flow is dominated by viscosity rather than momentum. Within the thermal boundary layer, heat transfer is dominated by conduction rather than convection. These differences between the boundary layer and the surrounding atmospheric air allow the transpired solar collector to effectively trap solar heat. Friction and heat transfer within the boundary layer are key to the operating principle of the transpired collector. Large holes far apart would not work. The dimensions and spacing of the perforations in the transpired solar collector must be small enough and close enough together to match the small dimensions of

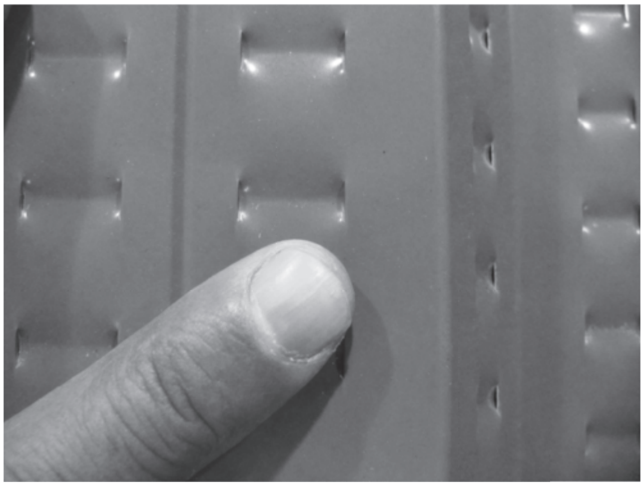


Figure 5-2. Close-up photograph of transpired solar collector shows small holes close together, created by knobby rollers that shear open slits. (Photo by the author).

the boundary layer. Heat trapped by the viscosity and conductivity of the boundary layer must be suctioned off through a near-by hole before it mixes with ambient air. Consequently, in order to minimize loss of heat to the ambient air, the holes in the transpired collector should be no farther apart than it takes for the boundary layer to fully develop. Really, a porous absorber media with no space between microscopic holes would be ideal, but current materials (aluminum or steel), manufacturing techniques, and required stiffness result in drilled, punched, or sheared holes, each with a diameter at least equal to material thickness, resulting in geometry similar to that shown in Figure 5-2.

Definition of Porosity

Porosity, P, is defined as the area of the opened holes divided by the total area of the absorber plate. For round holes arranged in a square pattern, the ratio is expressed as: $\frac{\pi d^2}{4p^2}$ where d is the diameter of each hole (m or ft) and the p is the "pitch," or the center-to-center spacing of the holes (m or ft). For example, 1 mm diameter holes 10 mm apart would have a porosity of $P = 0.008$. Note that porosity is dimensionless.

The porosity of transpired solar collectors is fabricated by dimpling the surface with knobby rollers to open up slits about 4.7 mm (3/16 in.) long and 0.79 mm (1/32 in.) wide at the center of the slit. Each roller creates slits to its right and left, two rows that are 35 mm (1 3/8 in.) apart with slits 19 mm apart in each row. The porosity calculated on this geometry is $P = 0.005$. This is similar to the plate shown in Figure 5-3.

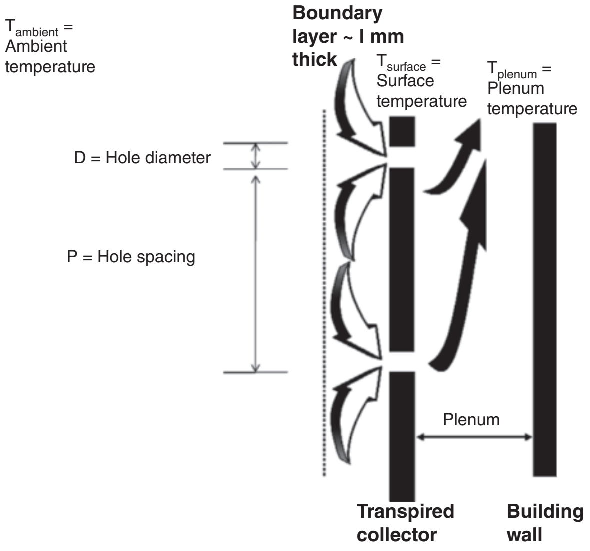


Figure 5-3. The thermal boundary layer of solar heated air is drawn in through tiny holes of a transpired solar collector before it mixes with ambient air. (Figure by the author).

Definition of v_{face}, face velocity (m/s) or (CFM/ft^2)

Face velocity is a key concept in solar ventilation air preheating system design and analysis. The face velocity is simply the total volume flow rate passing through the wall, divided by the transpired collector area. For example, consider a 46 m^2 (500 ft^2) transpired collector mounted on the south wall of a building. If a total volume flow rate of 0.94 m^3/s (2,000 CFM) of ventilation air were to be drawn through the transpired collector, the face velocity would be v_{face} = (0.94 m^3/s)/(46m2) = 0.02 m/s or (2,000 CFM)/(500 ft^2) = 4 CFM/ft^2, which is a value typically recommended by the author, although recent measurements suggest that doubling that to 8 CFM/ft^2 is necessary to ensure high efficiency. As the face velocity is lowered, a higher fraction of the heating load is met by solar, but with diminishing returns. At face velocity less that 0.01 m/s (2 CFM/ft^2), the heat loss off the face of the wall becomes excessive and above 0.05 m/s (10 CFM/ft^2) the additional fan power becomes wasteful. Thus a range of suitable values of about 0.01 m/s to 0.05 m/s (2 to 10 CFM/ft^2) is observed by designers. The designer does not specify the face velocity directly; rather the designer specifies the area of the transpired solar collector, and the face velocity results from dividing the fresh air requirement of the building by this area. Seeking a high fraction of the heating load from solar would indicate a large wall and low face velocity, but the economics are best with small wall and high face velocity.

Heat Transfer in Transpired Solar Collector

The transpired solar collector is a very efficient heat exchanger. But instead of transferring heat between two streams of air as most heat exchangers do, this one has only one air stream being heated—the heat is being provided by solar radiation incident on the surface of the heat exchanger. It is a radiant-to-air heat exchanger. The sunlight heats the absorber surface of the metal solar collector, and heat transfer to the air results from the surface being at a higher temperature than the air.

There are two ways of calculating net heat transfer across a heat exchanger: 1) the log-mean temperature difference method and; 2) the number of transfer units (NTU)-effectiveness method. The LMTD method is useful when both the inlet and outlet temperatures are known. However, in this case we know only the incoming ambient air temperature, so the NTU-effectiveness method is used (Incropera and DeWitt 2005).

Heat exchanger effectiveness, e_{hx}, is defined as the ratio of actual heat transfer to ideal heat transfer. Ideal heat transfer between the surface and the ambient air is an expression based on the air being heated from ambient temperature all the way up to the temperature of the surface heating the air:

$$q_{\text{ideal}} = mc_p(T_{\text{surface}} - T_{\text{ambient}}), \tag{5-1}$$

where
m = mass flow rate through the wall, kg/s
c_p = specific heat of air, around 1.00 kJ/kgK for the temperatures considered here
T_{surface} = the temperature of the absorber surface (C)
T_{ambient} = ambient air temperature (C)

And actual heat transfer is an expression based on the air being heated up to some temperature approaching but not achieving the temperature of the surface heating the air:

$$q_{\text{actual}} = mc_p(T_{\text{plenum}} - T_{\text{ambient}}), \tag{5-2}$$

where q_{actual} is the solar heat captured by the transpired collector and imparted to the ventilation air (watts).
T_{plenum} = the temperature of the solar heated air exiting the solar collector (C).

Effectiveness is expressed as a function of a dimensionless parameter called NTU for "number of transfer units."

$$e_{hx} = 1 - e^{-\text{NTU}} \tag{5-3}$$

NTU is the ratio of heat transfer to capacitance defined in this case as as the heat transfer coefficient (W/C, or Btu/h/F) divided by the specific heat of the air (W/C or Btu/h/F), so the ratio is dimensionless. Dymond and Kutscher (Dymond and Kutscher 1997) identified the NTU based on the parameters of interest in this situation as

$$NTU = \frac{kNu_d}{\rho v_{\text{face}} c_p d} \tag{5-4}$$

Where: k = thermal conductivity of air, around 0.026 W/mK for the temperatures considered here
ρ = density of air, around 1.1 kg/m^3 for the temperatures considered here
v_{face} = the "face velocity," defined as volume flow rate of air into the collector divided by the collector area = m/(ρA)
Nu_d = the Nusselt number, the ratio of convection heat transfer to conduction, also thought of as the dimensionless temperature gradient at the surface. Kutscher found a suitable correlation for the Nusselt number as a function of hole diameter and spacing and ambient wind speed and determined the constants in the equation by fitting the curve to data from wind-tunnel testing (Kutscher 1994). For values of porosity from 0.001 to 0.05 and Reynolds numbers from 100 to 2000, Kutscher's expression is:

$$Nu_d = 2.75\left[\left(\frac{p}{d}\right)^{-1.21} \text{Re}_d^{\,0.430} + 0.011\left(\frac{d}{p}\right)^2 \text{Re}_d\left(\frac{v_{\text{wind}}}{v_{\text{face}}}\right)^{0.480}\right] \tag{5-5}$$

Where p = the spacing between the holes (m),
d = the diameter of each hole (m)
Re_d = the Reynolds number, the dimensionless ratio of inertia to viscous forces = $[V_{\text{face}}\,(p^2/d^2)]\,d/\nu$ where ν is the kinematic viscosity of air, around 16.0×10^{-6} m^2/s for the temperatures considered here
V_{wind} = the wind speed (m/s) of the ambient air parallel to the collector.

REFERENCE

Thermal Properties of Air at 2 C (35.5 F)

The properties of air vary quite a bit with temperature, pressure and humidity. Table 5-1 lists some values for dry air at 2 C (35.5 F) which might be typical of a cold winter's day with a need for preheating ventilation air. This is just to give an idea of the numeric values of the properties in both metric and English units. The properties of air may be looked up in heat transfer books, or using Internet sites or computer programs, which give thermophysical properties as a function of altitude, humidity and temperature.

TABLE 5-1. THERMOPHYSICAL PROPERTIES OF DRY AIR AT 2C (35F)

ρ	Density	1.2475	kg/m^3	0.078	lbm/ft^3
c_p	specific heat	1.0065	kJ/kgK	0.240	Btu/lbmF
k	thermal conductivity	0.02415	W/mK	0.014	Btu/hrftF
ν	kinematic viscosity	1.37×10^{-5}	m^2/s	0.53165	ft^2/h
β	expansion coefficient	0.00367	1/K	0.00185	1/R

Source: Incropera and DeWitt 2005

Energy Balance for Transpired Collector

The first law of thermodynamics tells us that energy is not created or destroyed within the collector, and we can account for each type of heat gain or heat loss to calculate the useful heat delivered by the collector. Consider a transpired solar collector of area A_c (m^2) mounted on the vertical wall of a building. This area would be the total height times the width of the collector on the south wall. We have already discussed how to calculate the solar radiation incident on the collector, I_c (W/m^2), as the sum of direct-beam, diffuse, and ground-reflected radiation in chapter 2. The fraction of this absorbed and not reflected off the surface is the absorptivity, α. Thus the optical, radiant heat gain of the collector is $A_c I_c \alpha$.

Since heat lost off the face of the wall is drawn back in with the air, the primary mode of heat loss to the ambient is radiation. NREL researchers conclude that natural convection heat loss is negligible and wind-induced heat loss is negligible at face velocities greater than 0.05 m/s (10 CFM/ft^2), (Kutscher, Christensen, and Barker 1993). Their detailed treatment includes convective heat loss for when this condition is not met and also considers the view and temperature of the sky, ground, and other objects, which may be at different temperatures. But here for simplicity we represent all radiant heat loss to the ambient as $\varepsilon \sigma A_c (T_{surface}^4 - T_{ambient}^4)$. An expression for convective heat loss term is derived in Kutscher, Christensen, and Barker 1993 and the energy balance resulting from these terms is

$$q_{solar} = q_{useful} + q_{radiant\ loss} + q_{convect\ loss} \tag{5-6}$$

$$q_{solar} = I_c A_c \alpha \tag{5-7}$$

$$q_{useful} = m c_p e_{hx} (T_{surface} - T_{ambient}) \tag{5-8}$$

$$q_{radiant\ loss} = \varepsilon \sigma A_c (T_{surface}^4 - T_{ambient}^4) \tag{5-9}$$

$$q_{convect\ loss} = 0.82 \left(\frac{v_{wind} \nu}{v_{face}^2} \right) W[\rho c_p v_{face} (T_{surface} - T_{ambient})] \tag{5-10}$$

Where the terms in these equations that we haven't already defined are:

q_{useful} = the useful heat delivered by the solar collector (kW);

α = absorptivity of the surface paint in the short-wavelength solar spectrum, the fraction of solar energy absorbed by the surface.

ε = emissivity of the surface paint in the long-wavelength thermal spectrum

σ = Stephan-Boltzmann constant = 5.670×10^{-8} W/m^{2}K^4 (0.1714×10^{-8} Btu/hft^{2}R^4)

We wish to solve for $T_{surface}$ so that we can calculate the useful heat delivery, but we cannot solve Equation 5-6 directly for $T_{surface}$ because it is raised to the fourth power in the term accounting for radiant heat loss, Equation 5-9. This energy balance equation is solved by iteration: guess a value for $T_{surface}$ and then adjust that value until the right-hand side of Equation 5-6 equals the left-hand side.

ABSOLUTE TEMPERATURE (K OR R)

Temperature differences (T minus T) are often calculated in units of C, Celsius, or F, Fahrenheit. However, whenever temperature values are multiplied together or divided, they must be in units of absolute temperature: K, Kelvin, or R, Rankine. The conversions are as follows:

Degrees Kelvin = degrees Celsius + 273.15
Degrees Rankine = degrees Fahrenheit + 459.67
Further, 1 C = 1 K and 1 F = 1 R

Although the "quest for cold" continues, scientists have not been able to achieve absolute zero K (R) temperature in the laboratory. It seems as though the known laws of physics don't apply as theory attempts to describe the condition of matter at absolute zero temperature.

Having determined the value of $T_{surface}$ by iteration, the temperature of the transpired solar collector (sheet of metal) itself, we may now calculate the temperature of the air exiting the transpired collector and existing in the plenum between the collector and the south wall of the building

$$T_{plenum} = T_{ambient} + e_{hx}(T_{surface} - T_{ambient}) \tag{5-11}$$

The useful heat delivered by the solar collector may then be calculated as

$$\begin{aligned} q_{useful} &= m c_p (T_{plenum} - T_{ambient}) \\ &= m c_p e_{hx} (T_{surface} - T_{ambient}) \end{aligned} \tag{5-12}$$

The discussion above provides a way of calculating the useful heat delivery of the transpired solar collector as a function of hole diameter and spacing; the flow rate of air through the collector, the ambient wind speed, the incident solar radiation, the properties of the absorber surface (solar absorptivity and thermal emissivity) and the properties of air (density, specific heat, thermal conductivity, viscosity). Hole spacing is limited by the manufacturing equipment, so the parameters that a designer usually has control over are limited to the color and size of the wall needed to heat a certain amount of ventilation air, and the face velocity then results from the ventilation rate divided by the collector area.

Pressure Drop and Fan Power in the Solar Ventilation Air Preheating System

Understanding pressure drop across the absorber and through the connecting plenum and ductwork is important for both design of the fan and the performance of the solar ventilation air preheating system. In ordinary ductwork design, it is desirable to minimize pressure drop in order to save fan power, and this is the case here for the plenum and standard ductwork downstream of the absorber. However, it is essential to maintain some pressure drop across the absorber so that flow through the absorber area is uniform. Areas with less flow would experience more heat loss to the ambient.

The fan providing the ventilation air must overcome the pressure drop due to pulling the air through the small holes of the absorber, a pressure drop through the plenum, and a pressure drop due to the effect of airflow from the plenum into a duct. The buoyancy of the solar heated air also creates a pressure difference which may help or hurt the fan depending on where the fan is in relation to the height of the solar collector. Researchers at NREL (Kutscher 1994) provide an expression for the pressure drop as the air is drawn through the small holes in the transpired solar collector:

$$\Delta P_{\text{absorber}} = \frac{1}{2}\rho v_{\text{face}}^2 \left[6.82 \left[\frac{1-\left(\dfrac{\pi d^2}{4p^2}\right)}{\left(\dfrac{\pi d^2}{4p^2}\right)} \right]^2 Re_d^{-0.236} \right] \tag{5-13}$$

Which depends on hole dimensions and air properties, and depends very strongly on the face velocity of the air through the absorber. More recently Greg Barker of Mountain Energy Partners and Kosol Kiatreungwattana of NREL reported results of experiments to measure the pressure drop of holes created by using knobby rollers to shear open slits in the metal rather than punching round holes. The manufacturer can adjust the porosity by adjusting the penetration of the rollers and thus the depth of the slits. Panels with high porosity are known as "high flow" collectors and those with low porosity are known as *low flow*. Figure 5-4 shows the results of Barker's experiments for different values of porosity and for aluminum or steel (Barker and Kiatreungwattana 2011). The material should theoretically have no effect on pressure drop; perhaps the difference is in the size and smoothness of the holes and brought on by differences in ductility and strength of the material during the shearing process to open the holes. Barker used the form of the correlation of pressure drop across an orifice for his pressure drop curves, rather than the form of Equation 5-13.

$$\Delta P = k1[1/2\rho v_{\text{face}}^2 (v_{\text{face}}/\nu)^{K^2}] \tag{5-14}$$

Where k1 and k2 are the curve fit constants as listed in Table 5-2.

It is difficult to compare the theoretical pressure drop of Equation 5-13 with the measured pressure drop of Equation 5-14 because of the way porosity is represented in the two models. However, for medium porosity aluminum, perhaps the most common type, the two coefficients are k1 = 1895.279 and k2 = 0.308837. For a face velocity of 0.036 m/s (7 CFM/ft^2), an ambient temperature of 2.0 C (35 F); relative humidity of 0.30, and at 1 atm pressure, the density of air is 1.2 kg/m^3 and the pressure drop according to Equation 5-13 is 18 Pa for medium porosity aluminum, as compared to 20 Pa as calculated from equation 5-14 (using a porosity of 0.0079 in both equations).

TABLE 5-2. COEFFICIENTS ASSOCIATED WITH EQUATION 5-14 FOR DIFFERENT POROSITIES AND PLATE MATERIALS

Material/model	k1	k2
Steel		
Low porosity	35430	0.01777
Medium porosity	35430	–0.04245
High porosity	6910	0.1118
Aluminum		
Low porosity	23460	0.03787
Medium porosity	1895	0.3088
High porosity	37000	–0.1139

Source: Barker and Kiatreungwattana 2011.

Pressure drop across the absorber has important implications for design recommendations. Experts previously recommended a face velocity of 0.02 m/s (4 CFM/ft^2) as sufficient to maintain the recommended 25 Pa pressure drop across the collector. Figure 5-4 shows measured pressure drop for different porosities and face velocities measured by Barker. Based on Barker's measurement, the flow rate for medium porosity would have to be 0.04 m/s (7.9 CFM/ft^2) in order to maintain high efficiency. The implication is that projects seeking to get a large fraction of the ventilation heating load provided by solar, and thus needing a large collector area, need to specify a

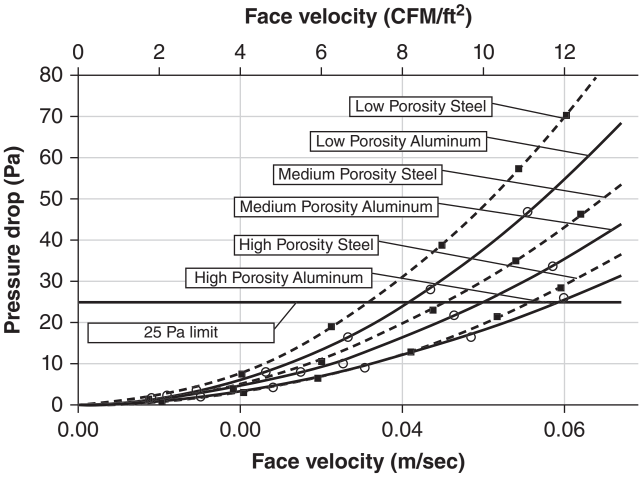


Figure 5-4. Pressure drop as a function of face velocity for varying porosity as measured by Barker at elevation of 5,400 ft and 22.5 C temperature. (Figure from Barker and Kiatreungwattana (2011), used with permission).

lower porosity than that often offered by suppliers. A pressure drop less than 25 Pa across the absorber may be overcome by wind and buoyancy effects, such that air comes out the holes rather than in, and reduces the efficiency of the heat collection

The pressure drop through the plenum and other ductwork is calculated using a form of equation that is very common in the literature regarding duct design:

$$\Delta P_{\text{plenum,ductwork,etc}} = \frac{1}{2}\rho v_{\text{face}}^2 \left[f \frac{L}{D_h} \right] \qquad (5\text{-}15)$$

Where

L is the distance across the plenum or the length of the duct (m), and D_h is the hydraulic diameter of the plenum or duct, defined as four times the cross-sectional area divided by the perimeter.

f = a dimensionless friction coefficient depending on the particular duct geometry.

TIP

Pressure Drop through Conventional Ducts and Plenums

Engineering textbooks and design manuals provide the value of the friction coefficient, f, for hundreds of duct shapes and describe how to calculate the pressure drop through the types of plenums and ductwork that exist in any air-handling system. Incropera and Dewitt provide two that are very common in the design of solar ventilation preheat systems (Incropera and DeWitt 2005).

For laminar flow in a duct of circular cross section f = 64/Re

For laminar flow in a duct of square cross section f = 57/Re

For the long, narrow plenum behind the transpired collector f = 96/Re

The Reynolds number in these relations, Re, is calculated as average velocity in the duct multiplied by hydraulic diameter and divided by kinematic viscosity of the air. The hydraulic diameter is defined as four times the cross-sectional area divided by the perimeter of the duct section.

The pressure drop associated with any other features of the ductwork such as elbows, turning vanes, expansions, or contractions also have friction factors associated with them that are tabulated in the literature and would be the part of the design of the ductwork connecting a solar ventilation preheat system to the conventional ductwork for a building.

There is a pressure difference resulting from buoyancy of the solar heated air in the plenum. If the air is withdrawn at the bottom of the wall, the fan would have to overcome this pressure difference, whereas if the air is withdrawn from the top of the wall this pressure difference would reduce the fan power required. Buoyancy can force solar heated air wastefully out of the holes near the top of the collector if the action of the fan is not sufficient to overcome the buoyancy. One supplier typically draws the air from the bottom of the plenum instead of the top in an attempt to defeat stratification of hot air within the plenum. Buoyancy occurs because of a difference in the air density between the cold ambient air and the hot air in the plenum. We could look up the density at each temperature, but it is easier to use a simplification called the Boussinesq approximation involving a thermodynamic property, β, which is the volumetric thermal expansion coefficient. For an ideal gas, such as air, the value of β is simply = 1/T, where T is *absolute* temperature in units of K or R. Thus at a temperature of 300 K (540 R) the value of β is 1/300 or 0.0033 1/K (0.00185 1/R) and the expression for the pressure difference due to buoyancy in the plenum is:

$$\Delta P_{\text{bouyancy}} = \beta (T_{\text{plenum}} - T_{\text{ambient}}) \rho_{\text{ambient}}\, g h_{\text{plenum}} \qquad (5\text{-}16)$$

Where g is acceleration due to gravity, which is 9.8 m/s^2 or 32.2 ft/s^2, and h_{plenum} is the vertical height of the plenum.

The air must be accelerated from the very slow face velocity V_{face}, to the velocity in the duct exiting the plenum. Newton's second law tells us that this requires the fan to do work. This kinetic energy may be recovered as static head elsewhere in the building ductwork, but here we calculate the pressure drop that the fan must maintain as:

$$\Delta P_{\text{acceleration}} = \frac{1}{2}\rho_{\text{duct}} v_{\text{duct}}^2 - \frac{1}{2}\rho_{\text{face}} v_{\text{face}}^2 \qquad (5\text{-}17)$$

Where v_{duct} is the average velocity of the duct from the plenum through the fan.

Thus the total pressure drop associated with the solar ventilation air preheat system may be added up as:

$$\Delta P_{\text{total}} = \Delta P_{\text{absorber}} + \Delta P_{\text{plenum, duct}} + \Delta P_{\text{bouyancy}} + \Delta P_{\text{acceleration}} \qquad (5\text{-}18)$$

In order to conserve fan power, each of these terms should be minimized except that some pressure drop is required to maintain uniform flow through the transpired collector surface ($\Delta P_{\text{absorber}}$). If this pressure drop were to be made too low, all the air would go through the wall near the intake duct and the corners of the collector wall would not get enough airflow to maintain the boundary layer effect and recover all the heat of the face of the wall. In early publications NREL researchers recommended at least a 50 Pa pressure drop across the absorber and reported that the resulting fan power is only about 4 percent of the collected solar energy (Kutscher, Christensen, and Barker 1993), although more recent results indicate that 25 Pa is sufficient (0.004 psi or 0.10 inch water column) for proper operation of the transpired collector.

Example Calculation of Transpired Collector Heat Delivery and Pressure Drop

Here we work through an example calculating the instantaneous performance of a transpired collector under certain conditions. Consider a transpired collector with a width of 15 m (50 ft) and an area of 46 m^2 (500 ft^2). The black paint on the wall has an absorptivity of 0.94 and an emissivity of 0.70. The plate is perforated with 1 mm holes 10 mm apart. The total ventilation rate is 0.94 m^3/s (2,000 CFM). The ambient conditions are: 500 W/m^2 (158 $Btu/ft^2/hr$) solar incident on the wall; 0 C (32.2 F) ambient temperature; and 1 m/s wind speed (11,808 ft/hr). We are asked to calculate the rate at which heat is delivered by the collector; the temperature of the solar preheated air; and the efficiency. We proceed through the equations of this chapter, and iterate on the energy balance of equation 5-5 to determine the unknown $T_{surface}$ using the iteration capability of a Microsoft Excel spreadsheet. The values resulting from each equation are listed in Table 5-3 in the order that they are calculated. We use the thermophysical properties of air at 2 °C (35.5 °F) although looking them up at each inlet temperature considered would improve accuracy.

TABLE 5-3. EXAMPLE CALCULATION OF THE SIZE, ENERGY DELIVERY, AND EFFICIENCY OF A TRANSPIRED SOLAR COLLECTOR IN A VENTILATION AIR PREHEATING SYSTEM

Transpired collector dimensions and surface properties			
W	Width of collector	15.2 m	50.0 ft
A_c	Area of collector	46.5 m^2	500.0 ft^2
p	Hole spacing	0.01 m	0.03280 ft
d	Hole diameter	0.001 m	0.00328 ft
α	Absorptivity	0.94	0.94
ε	Emissivity	0.7	0.70
Air flow rate			
V_{bldg}	Ventilation rate	0.94 m^3/s	2000 CFM
v_{face}	Face velocity	0.02 m/s	4.00 CFM/ft^2
m	Air mass flow rate	1.04 kg/s	8223 lbs/hr
Ambient conditions			
I_c	Solar insolation incident on the collector	500 W/m^2	158 Btu/hft^2
$T_{ambient}$	Ambient temperature	0 C	32.2 F
V_{wind}	Ambient wind speed	1 m/s	11808 ft/h
Heat-transfer parameters			
Re_d	Reynold's number based on hole diameter (VD/ν)	127	127
Nu_d	Nusselt number Equation 5-5	1.6	1.6
NTU	Number transfer units Equation 5-4	1.9	1.9
ehx	Heat exchanger effectiveness Equation 5-3	0.85	0.85

Energy balance			
T_{surface}		20.6 C	69.4 F
Q_{useful}	Useful heat collected Equation 5-5	18143 W	61904 Btu/hr
$q_{\text{rad loss}}$	Radiant heat loss Equation 5-8	3473.6 W	11851.8 Btu/hr
$q_{\text{conv loss}}$	Convective heat loss Equation 5-9	223.6 W	762.8 Btu/hr
q_{solar}	Radiant solar heat captured Equation 5-7	21840.1 W	74518.6 Btu/hr
Iterate until 0	Iterate values of T_{surface} until energy balance is equal Equation 5-5	0.0	
Results			
T_{plenum}	Temperature of solar heated air in plenum behind collector Equation 5-11	17.5 C	63.7 F
q_{useful}	Useful heat collected Equation 5-5	18143 W	61904 Btu/hr
η, Efficiency	Efficiency of the transpired solar collector Equation 5-19	0.78	0.78

We find that under these conditions, the solar ventilation preheat system would deliver energy at the rate of 18 kW (62 kBtu/hr) and heat the ventilation air from 0C (32.2 °F) to 17.5 °C (63.7 °F) temperature. Thus, even under the cold conditions considered here, the solar ventilation preheat system obviates the need for additional heating. The efficiency is calculated at 78 percent in this example.

Regarding pressure drop, the Reynolds number and pressure drop across the collector are as follows in Table 5-4. In this example we have not quite obeyed the 25 Pa pressure drop recommended by NREL for maximum efficiency.

TABLE 5-4. EXAMPLE CALCULATION OF THE PRESSURE DROP INCURRED BY THE TRANSPIRED SOLAR COLLECTOR OF THE EXAMPLE

$Re_{d,\text{hole}}$	Reynold's number based on Hole Diameter	4.06	4.06
$\Delta P_{\text{absorber}}$	Pressure drop across the transpired solar collector Equation 5-13	20.31 Pa	0.08 in. w.c.

Efficiency Curves

The efficiency, η, of the solar ventilation air preheating system is defined as the useful heat delivered by the solar collector divided by the incident solar power:

$$\eta = \frac{q_{\text{useful}}}{I_C A_C} = \frac{mc_p e_{hx}(T_{\text{surface}} - T_{\text{ambient}})}{I_C A_C} \tag{5-19}$$

All of the parameters in Equation 5-19 for efficiency are known or calculated, but we have to iterate to find T_{surface}, including the rather complicated effectiveness calculation, so the analysis lends itself to a computer.

Transpired solar collector efficiency does not vary much with incident solar I_c, and ambient temperature, T_{ambient}, if properly designed and under ordinary conditions. Figure 5-5 shows efficiency as a function of face velocity for different values of ambient wind speed. This figure was created using equations 5-5 to 5-13 and with the properties and conditions same as those of the Example Calculation of Transpired Collector Performance above. In order for this theory to be accurate, the pressure limit of 25 Pa must be observed, otherwise the flow is not uniform and the efficiency is less than that illustrated in Figure 5-5. The way to maintain the required 25 Pa pressure drop at low flow rates would be to specify a low porosity.

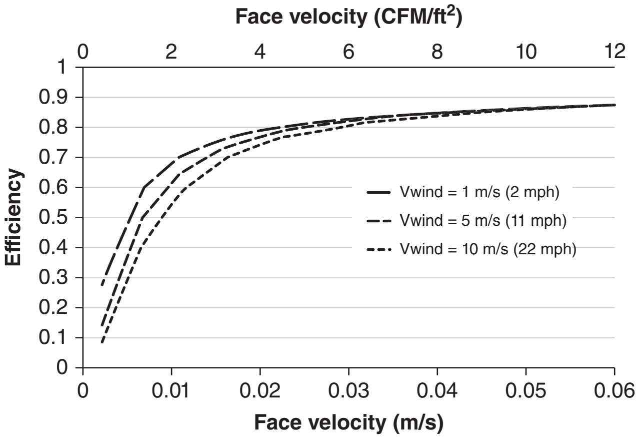


Figure 5-5. Calculated efficiency of a transpired collector as a function of face velocity for different wind speeds shows how low face velocity has a negative impact on efficiency.

SOLAR VENTILATION AIR PREHEAT SYSTEM SCHEMATIC

The schematic design of a solar ventilation preheating system specifies the size, type, and location of major components. A schematic diagram of a solar ventilation air preheating system is shown in Figure 5-6 and includes:

Transpired solar collector: collector area, m^2 (ft^2); porosity (diameter and spacing of holes); type and color of paint (and associated solar absorptivity and thermal emissivity). The height, width, color, and mounting location of the transpired solar collector must often be coordinated with a very large number of stakeholders who care about how the building looks.

Fan: total pressure drop, Pa (inches of water column), including both transpired collector and any associated ductwork; air flow rate of air at design conditions, m^3/s (CFM).

Bypass damper: size of opening and configuration of louvers; location of bypass damper assembly; type of actuator (electric or pneumatic);

Controls: the schematic design describes central or local controls and control sequence.

SOLAR VENTILATION AIR PREHEAT SYSTEM COMPONENTS

Compared to other types of solar systems, solar ventilation air preheating systems consist of very few simple components: the transpired solar collector, mounting and flashing hardware; bypass damper, actuator, and controls; and connecting ductwork. The system may have its own fan or may rely on the fan within the air handling unit to draw in the ventilation air.

Transpired Collector

Transpired solar collectors are typically made from aluminum at least 0.8 mm (0.032 inches) thick or steel at least 22 gauge thickness. NREL researchers have investigated nonmetal absorbers, and the Lubi System by Enerconcept Technolo-

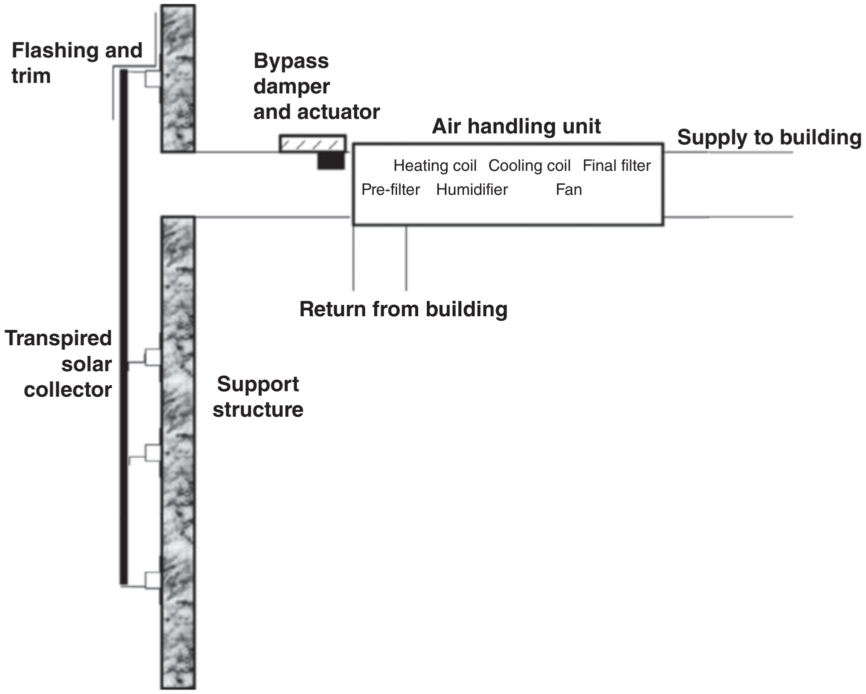


Figure 5-6. Schematic diagram of solar ventilation air preheat system. (Figure by the author).

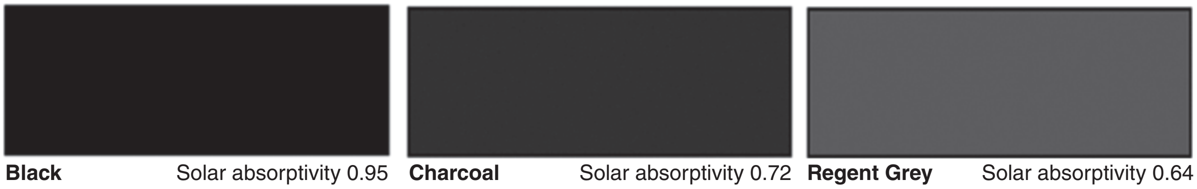


Figure 5-7. Absorptivity in the solar spectrum of three tints of gray offered by a supplier for transpired solar collector absorber surface. (Figure by the author from samples at solarwall.com).

gies uses polycarbonate absorber material. Perforated metal is a very common building element, but transpired collectors differ, in that the hole size and spacing and surface finish are specifically designed for low-cost manufacturing, longevity, and thermal performance. Because the edges of the slits or holes expose unpainted metal, aluminum is often the preferred material due to resistance to rust.

Early products were fabricated by punching or drilling holes. More recently, the transpired solar collectors are fabricated by dimpling the surface with knobby rollers to open up a slits about 4.7 mm (3/16 in.) long and 0.79 mm (1/32 in.) wide at the center of the slit. Each roller creates slits to its right and left, two rows that are 35 mm (1 3/8 in.) apart with slits 19 mm apart in each row. The holes are opened up while the sheet-metal stock is still flat, but after it is painted. Painting the sheet after the holes are opened would block the holes with paint. After the holes are opened, the sheet stock is bent into its profile shape to provide structural stiffness.

Because the transpired solar collector cannot be painted without blocking the tiny holes, selection of a paint which will maintain its properties for the economic lifetime of the collector is important. Polyvinylidene fluoride, or PVDF, is a polymer powder (trademarked KYNAR 500® PVDF or HYLAR® 5000 PVDF) which is used to give the paint extremely good resistance to degradation and good retention of color. Because painting it in the field would plug the tiny holes, such a premium paint is necessary to last the lifetime of the transpired collector.

Black is the best color for the absorber surface, with solar absorptivity on the order of 94 percent or higher. Other colors have lower absorptivity. Most paints reflect as much in the nonvisible infrared portion and ultraviolet portions of the solar spectrum as they do in the visible wavelengths. Some recent innovations improve on these optical properties of the paint. For most opaque surfaces, the radiation heat transfer surface properties absorptivity and emissivity have equal values. In fact, the second law of thermodynamics requires that these two be equal but only *at a given wavelength* of radiation. Performance is improved by taking advantage of the fact that the solar radiation to be absorbed is at a shorter wavelength than the thermal heat loss emitted from the surface. So called "selective surfaces" have a high absorptivity in the short-wavelength solar spectrum but a low emissivity in the long-wavelength thermal heat loss spectrum. The materials used to form selective surfaces in glazed collectors (blackened nickel oxide; semiconductor coatings) are not used in unglazed transpired collectors because they are fragile and don't hold up to the elements. However, manufacturers have developed paint pigments that have some selective properties, resulting in colors that have an absorptivity greater than their tint belies. Figure 5-7 shows the solar absorptivity of three shades of grey. The lighter shade, with an absorptivity of 0.64, would have about a third less solar heat delivery as the black paint with an absorptivity of 0.95. Suppliers offer over a dozen dark colors, including shades of green (0.71 to 0.90), blue (0.80 to 0.85), and red (0.59 to 0.69 solar absorptivity).

Trim and Flashing

It is best to locate the transpired solar collector away from doors and windows and to generally minimize the collector perimeter to be sealed. Trim and flashing around the perimeter of the transpired solar collector is very important. It is essential that the ventilation air flow be drawn in only through the perforations on the face of the collector and not around the edges. Overlapping seams between the panel sheets may be sealed with bituminous caulking compound, butyl tape, or other means provided by the supplier. Crack area should be minimized by careful installation of flashing around the perimeter. The flashing and trim must be attached to the wall and/or the support structure and not only to the siding. The crack between the supporting wall and the trim pieces must be caulked.

There is no evidence that rainwater penetrates the small perforations in the transpired solar collector. Still the wall surface beneath the transpired collector is generally required to be waterproof and holes are provided in the bottom flashing to allow water to flow out. Such holes should be minimal and fitted with insect screens to keep pests out of the plenum. Figure 5-8 shows a photograph of the drip edge at the bottom of a collector that is the condition at the bottom of the wall.

Support Structure

The transpired solar collector is attached to a support structure which also creates a plenum for heated air to flow to the fan. The distance between the transpired collector and the building wall depends on the expected air flow and distance to the nearest fan, but is not greater than 0.3 m (12 in) for structural and cost reasons. Air behind the transpired collector first travels vertically to the top of the wall, then horizontally to the nearest fan intake. Structural members supporting the transpired collector

Figure 5-8. Drip edge at the bottom of transpired solar collector. (Photo by the author).

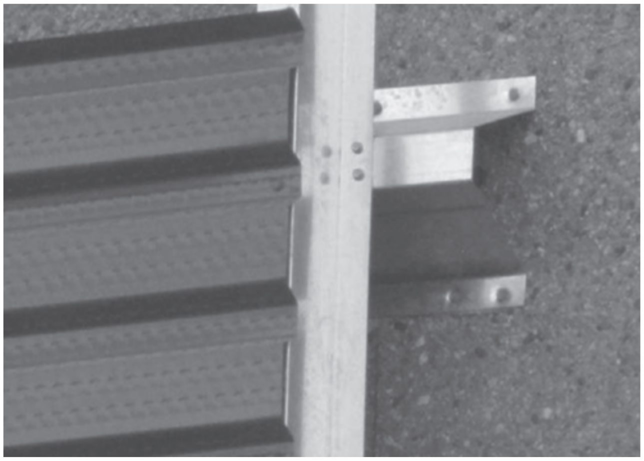


Figure 5-9. Transpired solar collector support structure attached to concrete wall. (Photo by the author).

must not block this air flow, and air flow must be balanced to ensure that air is drawn through the entire wall surface; otherwise, the efficiency of some parts of the wall may be reduced. If required to ensure uniform flow, the top portion of the wall may be made into a canopy that sticks out further from the building wall than the rest of the transpired solar collector.

If the building wall is concrete or masonry, then the supports can usually be fastened anywhere on the wall using anchors, such as shown in Figure 5-9. If the building wall is metal, then the supports must be connected to the girts, purlins, or columns using screws and not only to the metal siding. Similarly, for a steel or wood frame wall, the supports must be attached to the studs using screws and not attached only to the siding. A structural engineer specifies the type and number of fasteners for the loads (weight, wind) and allowable deflection.

The preheated ventilation air flows in contact with the building wall, which must satisfy all requirements related to moisture resistance and flame-spread. The buildings wall must have a waterproof and noncombustible surface such as brick, concrete masonry unit, metal, or any surface which meets requirements. The wall and insulation material should not be a material that could be food for mold or fungus. Since this wall will be covered by the transpired collector and not visible, the most inexpensive material that meets these requirements, such as unfinished concrete block, is often used. Figure 5-10 shows an example attachment to a metal wall in

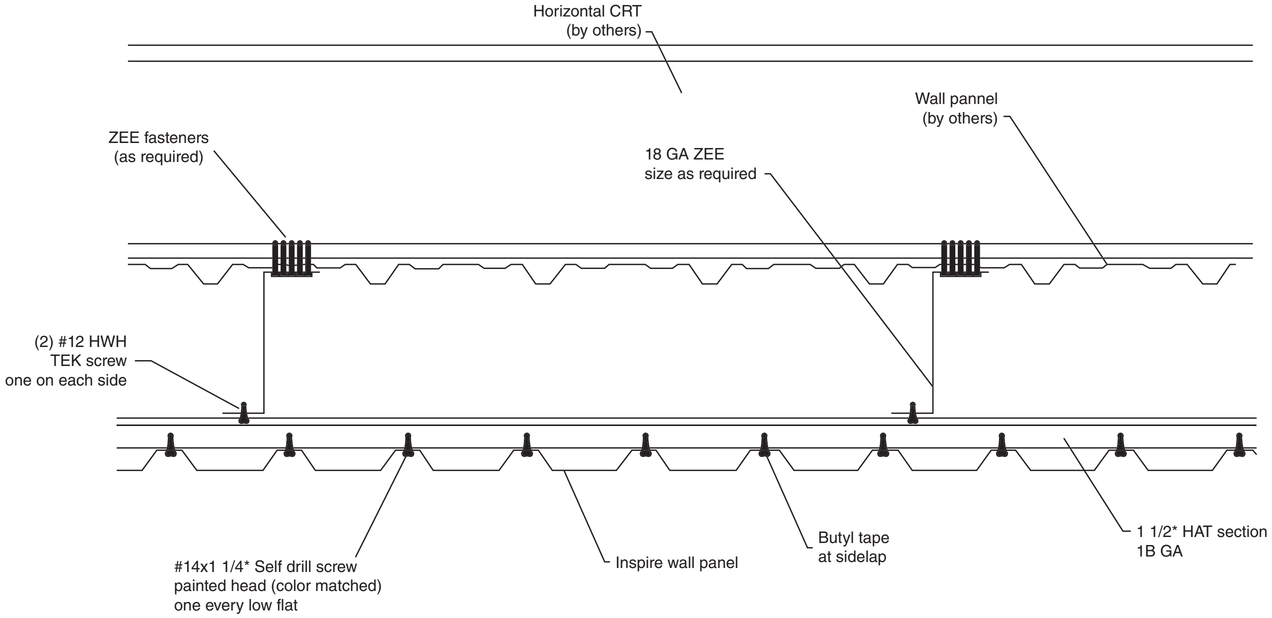


Figure 5-10. Schematic diagram of transpired solar collector support structure. (Drawing courtesy of Dick Bus, ATAS International)

new or retrofit construction. The surface of the conventional wall forms the backside of the plenum air duct behind the transpired collectors.

Fans

Fans are often supplied as part of a complete solar ventilation system by the same supplier as the transpired solar collector. The fan may also be the fan integrated into an air handling unit with a fresh-air intake or a dedicated outside air system. In spaces that have unit heaters (gas or steam heat units hanging from the ceiling), the ventilation air from the solar ventilation preheat system is sometimes introduced directly into the space by a stub duct or fabric duct and is further heated by mixing with room air and by the unit heaters. In this case a new in-line fan would be installed to move the new supply of ventilation air.

The fan power would be specified by the flow rate of air and the pressure drop for the entire fan system including: the absorber plate; the plenum and transition to duct; connecting ductwork; any filters, heating and cooling coils, and any other components of conventional air delivery system. Select a fan that meets design pressure and volume flow rate requirements. Performance of fans is certified by AMCA (Air Movement and Control Association) and publication AMCA 201 Fans and Systems describes how to account any system effects caused by nonuniform airflow into or out of the fan. Specify a fan class that is appropriate for the design operating point of flow and pressure.

The fan is selected based on the required volume flow rate and calculated pressure drop. Figure 5-11 is a conceptual illustration of a “fan curve.” The fan curve depends on the shape of the blades, but the same fan will have a different curve if driven by a different motor. Specify a fan/motor combination that has its maximum efficiency near the flow and pressure difference calculated for the system. The transpired solar collector, plenum, plenum to duct transition, and bypass damper add to the pressure drop of conventional system components (heating and cooling coils, filters, etc.) and ductwork to determine the total requirements of the fan.

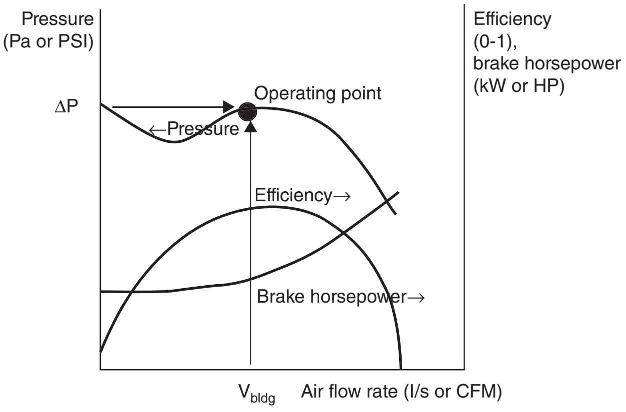


Figure 5-11. This conceptual fan curve shows how a fan that has a high efficiency near the operating point of flow rate and pressure drop would be selected. (Figure by the author).

Because of the large area of the collector, the additional fan power imposed by the transpired solar collector is a small fraction of the overall fan power required of a ventilation system. A conventional fan system may have a static head of 125 to 750 Pa (0.5″ to 3″ of water column); whereas the pressure drop across the transpired solar collector is on the order of 25 Pa (0.10 “of water column). A size and type of fan are selected by finding a fan with a fan curve that maintains the required pressure for a given flow rate.

For a pressure drop of 25 Pa (0.10″ of water column) and a face velocity of 0.02 m/s (4 CFM/ft^2), the power required to draw the air through the holes of a transpired collector would be 0.5 W/m^2 (power per unit of transpired collector area). Dividing by a fan efficiency of 50 percent would indicate that about 1 W/m^2 (0.1 W/ft^2) of electric power use is imposed by the collector itself. Including the friction of plenum and additional ducts brings the total fan power required to approximately 2.5 W/m^2 (0.25 W/ft^2) to 5.0 W/m^2 (0.5 W/ft^2) depending on the length and complexity of the ductwork.

Refer to NFPA 70, National Electrical Code, or applicable code or standard for motor controller and disconnect location requirements. Provide access to the fan and motor to measure voltage, amperage, and fan speed during testing.

Bypass Damper

The requirement for ventilation air is usually based on standard requirements and is required in both winter and summer. Certainly we don’t want to preheat the ventilation air when the ambient air is already warm, but even on cold days the internal heat gain such as lights, computers and people in the building may obviate the need for additional heating. Some buildings, such as computer data centers, have the air conditioner cooling all the time, and the solar heat is not welcome. However, most buildings need to modulate back and forth between using the solar preheated air and drawing in unheated ambient air, and this function is provided by an actuated bypass damper. An electric actuator would open or close the bypass damper based on a control signal from a thermostat in the space or from a building control system.

Some air handlers recirculate a large percentage of the air as a means to deliver heating and cooling to a space, and add perhaps 20 percent of the total moved by the fan as outside air to replace exhaust air. Since the temperature of the air returning from the space may be higher than the desired space temperature, the temperature of the “mixed air” (the 80 percent recirculated air and the 20 percent outside air mixed together), would control the bypass damper. For many hours of the year, the building will be able to use the free cooling of the cold incoming ventilation air to cool the building and the bypass damper would be open.

Controls

The configuration of controls depends on whether the transpired solar collector is preheating for direct ventilation of the space or delivery to the first stage of an air handling unit.

In the case of direct ventilation of the space, the bypass damper may be controlled by the space thermostat: if the last call from the space was for heat, then the bypass damper is closed and air is preheated by the transpired collector. If the last call from the space thermostat was for cooling, then the bypass damper is open and fresh air is drawn directly in by the fan without solar heating. If the space does not have cooling equipment, then the bypass damper is actuated when the space reaches a maximum set temperature as may be implemented with a temperature switch. Measuring a single temperature representative of a large open space is challenging, especially since unit heaters suspended from the ceiling often provide the primary source of heat for the space. The sensor or multiple sensors should be located to measure the coldest temperature in the space, not directly affected by the hot air blowing out of a unit heater.

For transpired solar collectors preheating for an air-handling unit, the control logic is: if the mixed air temperature is low enough to start the heating coil of the air handling unit, then the bypass damper would close and ventilation air would be drawn in through the transpired collector. If the mixed air temperature rises high enough to start the cooling coil, then the bypass damper would open and draw in fresh air without preheating. This control can be achieved by a simple thermostat or by interlocking with cooling and heating valve status. The bypass damper remains closed until the cooling set-point is exceeded and then it stays open until the mixed-air temperature drops below the heating set-point.

Fan power may be conserved by bypassing the transpired solar collector when solar heat gain is insufficient to justify the fan power. This may be achieved by an enabling switch based on: temperature difference between the ambient air and the air from the transpired collector plenum; by photocell control; by time-clock control; or by more sophisticated controls.

The control strategies above all assume that the required amount of fresh outside air is constant, and it is only a matter of deciding whether to preheat or not, so the bypass damper is either fully open or fully closed. Proportional controllers have also been used to modulate the position of the bypass damper to maintain a constant delivery temperature. Although perhaps useful for those pursuing net-zero energy use or other superlative goals, reducing the air flow through the wall in an attempt to supply a given temperature slows down the air too much—compromising the operating principle of the collector—and results in lower system efficiency. The design recommendation is to pass all required ventilation air through the collector and allow the temperature delivered by the collector to vary.

The control strategies above are described in terms of simple thermostats, temperature switches, or interlocking with other controls. However, control is very often integrated into a computerized building control system where more sophisticated control logic may be implemented. An example of a programmable sequence from an industrial building application proceeds as follows: if the outside temperature is below 16°C (61°F) and time is between 7:00 a.m. and 7:00 p.m. and building temperature is below 18°C (65°F) and solar-heated ventilation air temperature is more than 2°C (4 F) above building temperature, then the bypass damper is closed and solar-heated air is delivered to the building; if the building temperature is 18°C (65°F) or greater and the outside air is 2°C (4°F) lower than the internal temperature, then the bypass damper is open and unheated fresh air is delivered; if the solar ventilation air temperature is between the building temperature and 2°C (4°F) above, then the the bypass damper modulates to maintain the minimum amount of outside air at 18°C (65°). The heating coil will activate if the damper control cannot maintain the air at this set-point.

Connecting Ductwork

The fan draws air in from the plenum between the south wall and the transpired solar collector. An air duct is needed connect this plenum to the first stage (mixing box) of an air-handling unit with the fan, or duct it from the plenum through an in-line fan directly into the space via a stub duct or fabric duct. For metal ductwork, specify the duct gauge and reinforcement hanger spacing in accordance with SMACNA construction standards for round duct and rectangular ducts.

Definition of Mixed-Air Temperature C (F)

The temperature of the recirculated air returning from the heated space mixed with the fresh outside air coming in is called the mixed-air temperature. This is the air that would be then heated by a heating coil. Often some "free cooling" is desired due to heat gain from busy people, lights, and computers in the space. In this condition cooling is being provided by the fresh air, and solar heating is not wanted. Thus, the temperature controlling the actuation of the bypass damper should be the mixed-air temperature, not the ambient air temperature.

DESIGN CONSIDERATIONS

Design of a solar ventilation air preheating system involves balancing several considerations. Solar ventilation air preheating is very cost-effective, but the benefits diminish as the design tries to get a larger fraction of the heating requirement from solar. Design considerations are: provide area for mounting transpired solar collector on the wall elevations; maintain the desired pressure drop and uniformity of flow across the area of the collector; avoid sources of pollution; avoid shade; provide route of air duct from south wall to air handling unit; and provide control for actuation of the bypass damper.

Collector orientation: Collector orientation is a compromise between capturing as much sun as possible and capturing it when the heat is needed. The optimal orientation is usually considered to be mounted flush on the vertical side of the building facing directly toward the equator (south side in the Northern Hemisphere; north side in the Southern Hemisphere). However, many buildings call for heat in the morning, indicating that facing the wall toward the equator but also to the east is beneficial. In contrast, by afternoon, most buildings are already warm by virtue of the busy people inside, indicating that facing the wall to the west would diminish savings. For drying operations, a tilt from the horizontal equal to the local latitude and in the direction toward the equator would maximize year-round heat delivery, although the tilt angle could be optimized for the months that crops are to be dried.

DESIGN TIP

Balance Wall Area, Flow Rate, and Porosity

The design objective of maintaining pressure drop and uniform flow across the area of the transpired collector involves balancing the effect of three parameters:

A_c: Area (m^2 or ft^2) of the transpired collector
V_{bldg}: Volume flow rate of air, m/ρ (l/s or CFM);
P: Porosity of the transpired solar collector.

Usually the volume flow rate of air is specified by the building requirements. And often the porosity is limited to one of three offered by the supplier. So the area of the collector, A_C, is usually the parameter adjusted by the designer to accommodate the other two and achieve the recommended face velocity, $v_{face,}$ and minimum recommended pressure drop of 25 Pa. This approach has resulted in a wall area that is too small to meet a large fraction of the building's ventilation heating load. So designers should keep in mind that it is possible for the manufacturer to adjust the size of the holes in manufacturing (spacing of the holes, the other parameter affecting porosity, is difficult to adjust), and designers should request a lower porosity from suppliers to maintain uniform flow if they wish to intstall a large collector area and achieve a higher temperature rise in the collector.

Collector area: Whether using detailed computer tools or simple calculations, collector area is the principal design parameter. To maintain collector efficiency, 1 m^2 (10.76 ft^2) of collector area is needed per each 0.004 m/s (per each 4 cubic feet per minute of ventilation air), and to maximize efficiency higher flow rates are indicated, as high as 0.001 m/s (10 CFM/ft^2)

The total amount of air flow is generally established by the building's ventilation requirements (l/s or CFM). Making the collector larger would intercept more solar radiation and reduces the face velocity (m/s or CFM/ft^2), resulting in higher delivery temperature and more savings in fossil fuels. But the size of the wall will be limited by one of several effects to the minimum of:

- The size which delivers the optimal amount of heat as a fraction of ventilation heating load
- The available wall area on the side of the building facing the equator
- The size which maintains recommended pressure drop and efficiency

As we consider a larger collector area, there will be more hours in the year when the temperature rise exceeds the desired delivery temperature, and the excess heat is wasted. Also, the operating principle of the transpired collector breaks down if the pressure drop across the wall drops to less than 25 Pa resulting in reduced efficiency, so Barker recommends sizing the wall such that the face velocity is not less than 0.03 m^3/s (6 CFM/ft^2), and as much as 0.06 m^3/s (12 CFM/ft^2) for a material with high porosity (Barker and Kiatreungwattana 2011). Strict adherence to this guideline would maximize collector efficiency, but energy savings goals may require the collector to be larger, albeit at the expense of a lower efficiency. As a compromise to balance these objectives, the author recommends that a size resulting in a face velocity of 0.04 m/s (4 CFM/ft^2) delivers substantial energy savings while maintaining efficiency above 40 percent.

Figure 5-12 shows a thermal image of the temperature of a transpired solar collector showing nonuniform air flow through the wall near the corner.

Suppliers offer a "sandwich assembly" or "plenum wall" with both sides of the plenum (transpired front and sheet-metal back) which could be used as a screening wall around rooftop equipment, such as shown in figure 5-13.

Avoid sources of pollution: Avoid locating the transpired solar collector where pollution may be drawn into the ventilation air, such as truck loading docks. Where such is unavoidable, projects have included alarms and controls to avoid drawing in pollution with the ventilation air.

Collector attachment to wall: The transpired solar collector must be supported by a wall which meets all structural, insulation, moisture, and flame requirements. However, since this wall completely covered by the transpired solar collector

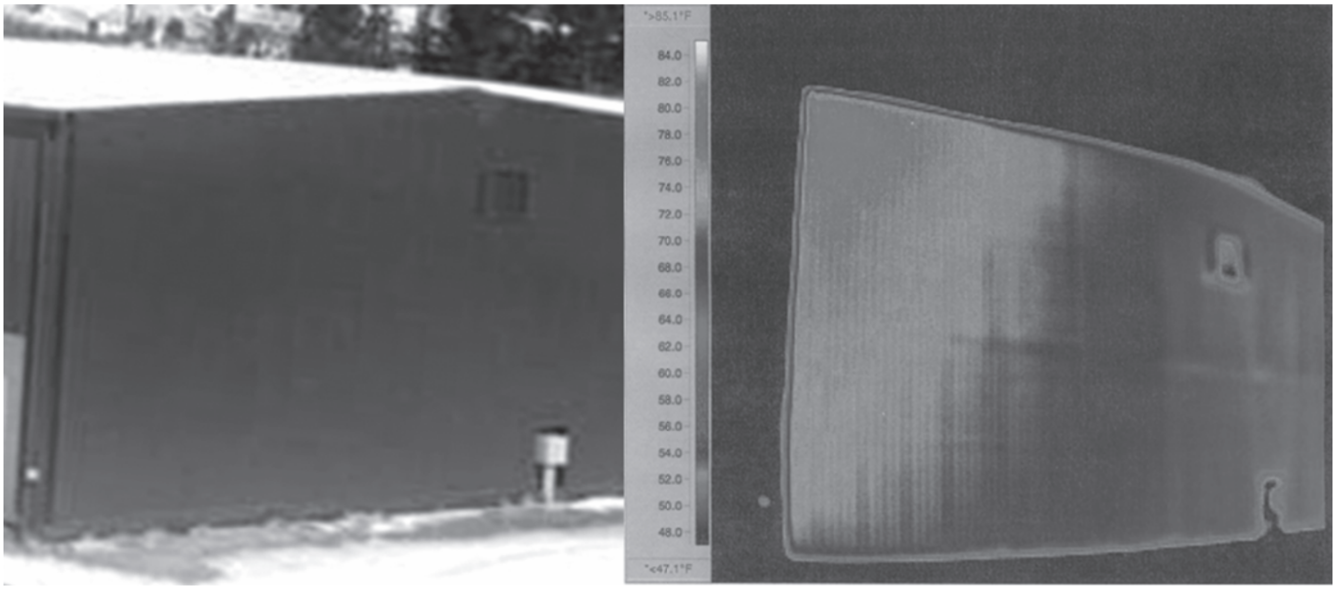


Figure 5-12. Thermal image of transpired solar collector on a water treatment building in Leadville, Colorado. The higher temperature in the upper left corner indicates that part of the collector is not getting enough air flow and suffers higher heat loss. (Image by Ed Hancock, used with permission).

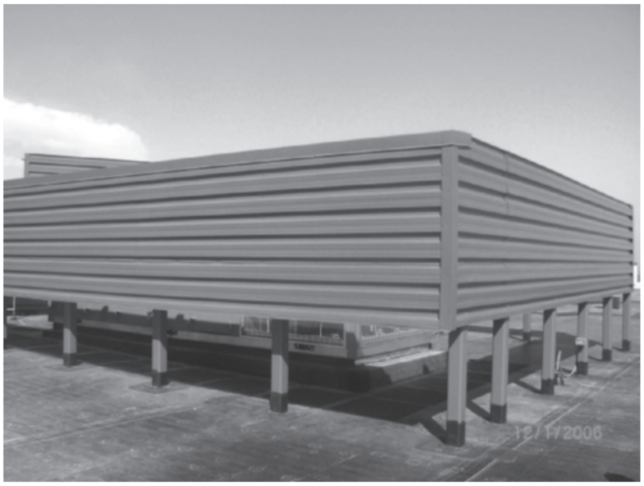


Figure 5-13. Example of transpired solar collector mounted on screening wall around rooftop equipment, rather than on a vertical wall, at Carbon Valley Regional Library in Frederick, Colorado. (Photo by Renee Azerbegi, courtesy of Ambient Energy Inc.).

and flashing, its appearance is not important and is often bare block or some inexpensive exterior finish. The transpired solar collector is attached to the support structure with fasteners visible, although some suppliers may be able to hide fasteners based on techniques developed to finish metal buildings.

RECOMMENDED APPLICATIONS

Industrial Ventilation

Ventilation of rooms in which industrial processes take place is perhaps the best application of the transpired solar collector system because the ventilation requirement is independent of occupancy and often constant throughout the day and throughout the week.

Commercial Ventilation

Commercial buildings are often closed on weekends and holidays, reducing the savings of this technology because ventilation air would be off or at a minimum when solar heat is available on holidays. Unlike electic batteries or hot water storage tanks, there is no way to store the solar heated ventilation air. Ventilation rate is also often reduced in response to low occupancy. Further, heating coils are often controlled in response to mixed-air temperature, where the cold fresh air is at least partially warmed by mixing with return air from the space. Commercial buildings often have dense occupancy and high internal heat gain, reducing the need to heat ventilation air. Still, for many commercial buildings, solar ventilation air preheating has proven to be cost-effective.

Drying Operations and Industrial Applications

Solar drying using a porous solar absorber media appears in the literature as early as 1940. An installation in Germany

Interview with Greg Barker

Greg Barker's business card has the title "Rocket Scientist," which is in jest but is taken seriously when people see his array of complicated instruments, many of which he made himself. He has a bachelor's degree in mechanical engineering from Tufts University and a master's degree from the University of Colorado in Boulder. He was involved in the initial development and testing of the transpired collector at the National Renewable Energy Laboratory (then the Solar Energy Research Institute) in Golden, Colorado. Since then he has worked as a consultant specializing in the measurement and simulation of alternative energy systems, from home-sized PV systems to industrial-scale solar steam generation systems. Over the last 20 years Mr. Barker has coauthored several papers on transpired collector technology, developed a TRNSYS computer simulation model of the transpired collector, and compared model prediction to measurement for several installed transpired collector ventilation preheat systems.

Figure 5-14. Photograph of Greg Barker measuring pressure drop with a cup held over a hole in the transpired solar collector. (Photograph courtesy of Ed Hancock).

You've measured the performance of more solar ventilation preheat systems than anyone I know. Well, how about it?...do they work?

They always work to some degree or another, but the trick is to design the system properly to realize the high thermal efficiency of which the system is capable. High thermal efficiency generally implies high cost-effectiveness, which is what the designer is generally striving for. Unglazed collectors are most efficient when the absorber is relatively cool, which happens when the air is being drawn through the collector at a high rate. The result is a small rise in temperature, not generally suitable for space heating but perfect for preheating ventilation air, where any temperature rise above outdoor temperature translates to energy saved. So far I have only measured the performance of one transpired collector system which had a high enough flow rate to realize efficiencies of about 60 percent, and this was solely due to air flow rate. All the other systems I have tested had much lower efficiencies, and thus lower cost-effectiveness, because they were designed to have a low enough flow rate that the air entered the building above room temperature. I think this is done because there is often a misconception on the part of a building manager that the warmer the delivered air is, the more efficient the collector is. So if you design a system for high efficiency, and it is 10 F outside, and the air is being delivered at 30 F, the building manager feels that cold 30-degree air and thinks the collector isn't working well. In fact it's saving in a cost-effective way energy that would otherwise have been used to heat the ventilation air after it entered the building. In general, the rule is that unglazed, transpired solar collectors are not cost-efficient if they are used for a purpose that requires a large rise in air temperature, as is the case for space heating. They are very cost-efficient if even a small temperature rise results in energy savings, as is the case for ventilation preheating applications.

In your recent paper regarding testing at a facility, you report that walls without enough flow rate per unit area (face velocity) suffer a low efficiency, why is that the case and how did you figure that out?

We measured the energy delivered by measuring the air flow rate out of the collector and multiplying the flow rate by the temperature rise from the outdoor air to the delivered air. We also measured the total solar radiation striking the collector. The efficiency was defined as the delivered energy divided by the total solar energy striking the collector. In this particular installation we were able to vary the air flow rate to see the effect of flow rate on efficiency, and we found that the efficiency drastically decreased with decreased flow rate. There are two separate phenomena that affect efficiency at low flow rates. The first is that, even for a collector whose flow rate into the collector face is uniform over the entire collector, a lower flow rate leads to a higher absorber temperature, which leads to exponentially higher heat loss from the absorber to the surroundings via infrared heat loss. The second phenomenon is that of nonuniform flow due to low pressure drop from outside to inside the collector. There are several causes of nonuniform air flow: wind impinging on the building, thermal "stack effects" where the air behind the absorber tends to rise due to natural convection, and the fact that usually the air is drawn into the building from one or more ducts behind the collector; it is not drawn uniformly from the entire back plane. If the pressure drop is above about 25 Pa, all of these causes are mitigated. The flow is uniform, and therefore the absorber temperature will be uniform under most conditions, even windy conditions. As the flow rate is decreased, the pressure drop decreases, and the flow becomes less uniform. In the mildest case, there will be hot spots farthest from the points at which the air is drawn into the building, leading to a slight decrease in efficiency since the heat loss increases exponentially with absorber temperature rise. In moderate cases, if wind impinges on the building from a direction such that the pressure at the outside of the absorber is lower than the pressure behind the absorber, air will flow out of the absorber in places, decreasing the overall efficiency. In extreme cases, if the pressure drop is extremely low, air can flow out of the collector near the top due to stack effects even if the wind is not blowing.

On the other hand, the overall flow rate is fixed by the building requirement, so to maintain the 25 Pa you need to make the wall smaller. Doesn't that reduce your solar contribution and burn more fossil fuel?

Making the wall smaller will decrease the total amount of solar energy striking the collector, but it will increase the efficiency at which the energy is collected and it will decrease the capital cost of buying and installing all of that collector area. In some cases, notably in windy areas, halving the collector area can double the average efficiency, so the same amount of energy is collected in either case.

So how should people trying to get a large fraction of their load from solar, even "net zero," approach the design of a solar ventilation preheat system?

My advice is to always design the system to maintain at least a 25 Pa pressure drop across the absorber to make the flow uniform under all conditions. After that the most cost-effective design is able to make use of any temperature rise above outdoor air temperature; ventilation air preheat is a good example. If cost-effectiveness is not the primary concern, the flow rate can be reduced to increase the delivered air temperature. If you want to increase the solar fraction, you will have to use absorbers with porosities lower than those commonly available as you move to larger collector areas in order to maintain the 25 Pa pressure drop.

What has this real-world experience taught you that you can't find in textbooks?

I find it's hard to convince people that a solar collector that is delivering cold air (but warmer than outside air) is working well because it's counterintuitive. I've often thought that a well-designed package would include the unglazed transpired ventilation preheat system and an in-line "post-heater," or ducted to an air-handling unit, that would bring the delivered air temperature up to room temperature. This way no one would have to feel that "cold," albeit solar preheated, air.

uses transpired collector to preheat combustion air for a utility-scale boiler, and it would be useful in many such industrial applications, such as laundry drying facilities, paint and curing facilities, and any application that can use heated air. Note that some processes compress air before it is heated, and a solar heating of the air would decrease the density of the air and increase the compressor work—so solar ventilation preheat is not recommended in applications such as gas turbines, where the incoming air is compressed before being heated.

A detailed discussion of the heat and mass transfer of drying is beyond the scope of this book, but simple relationships for common geometries and materials to be dried may be found in the literature. Pressure drop through the material to be dried may be calculated by the Darcy equation, which is the equation of motion for fluid through a porous media, or by empirical data, and would add to the required fan power. Placing the material to be dried between the fan and the transpired solar collector offers a lower pressure to enhance drying, but provide enough pressure at the inlet of the fan for proper fan suction. Solar heated air should be directed through, not over, the bed of material to be dried.

Household produce is often dried in developing countries by laying it out in the sun. A simple crop dryer was built by the author using a perforated flexible plastic cover and a solar-powered fan. The perforated cover also protected the food against dust and diesel soot; pests; and theft.

ESTIMATING THE COST OF A SOLAR VENTILATION AIR PREHEAT SYSTEM

Initial Cost Estimate for Solar Ventilation Air Preheat System

A heuristic cost estimate based on cost information from historical projects is used before the details of a design are known. Once the schematic design specifies the size and type of components, a detailed cost estimate may be prepared.

Simple Heuristic Cost Estimate

Discussions with suppliers indicate that the transpired solar collector itself (sheet metal painted, perforated, and profiled) costs around \$150/m^2 (\$14.50 per square foot). In a "product of the week" posting titled "Transpired Solar Collector Performance: More Than Hot Air" by Brent Ehrlich, products editor at BuildingGreen.com (Ehrlich 2011) includes cost opinions of an unglazed metal transpired system at between \$150/m^2 (\$15/ft^2) and \$200/m^2 (\$20/ft^2). In the same article, Enerconcept states that an installed glazed transpired Lubi system costs \$22 to \$25 per square foot, although they claim a higher performance than the unglazed collectors. The ATAS website

TABLE 5-5. EXAMPLE COST ESTIMATE FOR SOLAR VENTILATION PREHEAT SYSTEM

Solar ventilation air preheat system 30.48 m (100 ft) wide by 4.88 m (16 ft) tall; total wall area 148 m^2 (1,600 ft^2);	**Quantity**	**Unit**			**Material**	**Installation**	**Total**
Transpired solar collector; 0.032 aluminum; black PVDF finish; 0.95 absorptivity; each 41.25 in wide x 16 ft long	149	m^2	1600	ft^2	$23,200	$1,500	$24,700
Hat-shaped support frame; 0.05 aluminum; 12 foot length;	122	m	400	ft length	$532	$3,000	$3,532
Subgirt support frame; 0.05 aluminum; 12 foot length	152	m	500	ft length	$475	$1,000	$1,475
Perimeter trim; straight; 0.05 aluminum;	71	m	232	ft length	$2,204	$2,000	$4,204
Corner trim perimeter; welded; 0.05 aluminum;	4	Each			$176	$500	$676
Adhesive closure Tape; 50 ft roll	5	Rolls			$390	$0	$390
Butyl air-seal tape; 50 ft roll	10	Rolls			$180	$0	$180
Concrete anchor attachments	800	Each			$800	$0	$800
Tek-screws; metal; #14;	2000	Each			$400	$0	$400
Touch-up color pen	1	Each			$10	$0	$10
Touch-up color 2-oz.	1	Each			$24	$240	$264
Bypass damper; aluminum; 40 in by 40 in	1	Each			$920	$300	$1,220
Bypass damper Actuator; 100 to 240 V; with relay	1	Each			$300	$240	$540
Bypass damper Thermostat; 24V power supply	1	Each			$100	$120	$220
Fan; 6400 CFM	1	Each			$1,770	$1,200	$2,970
Site mechanical: ductwork	16	hours			$6,000	$640	$6,640
Site electrical: fan, damper and controls	24	hours			$3,000	$960	$3,960
Design							$4,000
Construction management							$4,000
Continency							$4,000
						Total	$64,181
					Unit cost	$431.62	/m^2
						$40.11	/ft^2

(ATAS 2011) gives an approximate cost of \$140 to \$170/m^2 (\$14 to \$17/ft^2) of collector area, installed, but with fans, dampers, and ducts in addition to this. Based on this information and on experience with projects, the author offers \$400/m^2 (\$40/ft^2), as representative of small to medium sized systems as described in the following basic cost estimate.

The installed cost of the solar energy system would thus be

$$C_{initial} = c_{unit}A_c \tag{5-20}$$

Where c_{unit} is the unit cost (\$400/m^2 or \$40/ft^2) and A_c is the collector area.

Detailed Cost Estimate

A detailed cost estimate is prepared by assigning a cost to each component in the schematic design and also estimating the cost for labor to install the component. Some costs such as design, project management, overhead, and profit are added as fixed costs or as a fraction of project cost. Table 5-5 lists an example of such a detailed cost estimate.

TIP

Ventilation Rate, $V_{bldg,}$ l/s (CFM)

Ventilation rates for different types of space are established by minimum code requirements or green building standards in excess of minimum code requirements. There are several published standards that involve specification of ventilation rates. ASHRAE Standard 62.1 is observed in many jurisdictions in the US. It specifies a sum of a per-floor-area value and a per-person value, at least 5 L/s/person (10 cfm/person). For example, the sum of these might vary from 0.001 m/s (0.1 CFM/ft^2) of floor area for an inactive warehouse, 0.0034 m/s (0.34 CFM/ft^2) for a typical office space, and to 0.01 m/s (1 CFM/ft^2) per unit of laboratory floor space. The US Green Building Council LEED Rating System awards one point for exceeding the ASHRAE 62.1 rate by 30 percent. ACGIH *Industrial Ventilation, a Manual of Recommended Practices*. 25th ed., 2004, 24th ed., 2001 requires ventilation that depends on the rate of release of air contaminants within the space, which is the approach taken in industrial or laboratory settings. National Fire Protection Association NFPA-45–2004 results in 4 to 8 air changes per hour (ACH), depending on occupancy. ASHRAE Lab Guide-2001 and OSHA 29 CFR Part 1910.1450 result in 4 to 12 air changes per hour, and ANSI/AIHA Z9.5 also relates to laboratory personnel protection. Establish your requirement for outside ventilation air prior to sizing the solar ventilation air preheating solar collector. The building owner or responsible party must always specify or agree to any calculated value of the ventilation rate.

SIMPLE HAND CALCULATIONS FOR SIZE AND PERFORMANCE OF A SOLAR VENTILATION AIR HEATING SYSTEM

Sizing the area of the Solar Collector

The size of a solar ventilation air preheating system is best determined by life cycle cost optimization, considering the diminishing returns of making the collector larger. But that is a complicated analysis requiring computer simulation. As a simple hand calculation we consider a simple sizing approach based on satisfying a number of constraints of the design criteria. For a given amount of ventilation air, the suggested size is given by the following equation.

$$A_c = V_{bldg} / v_{face} \tag{5-21}$$

Where:
A_c = solar collector area (ft^2 or m^2), might be limited by available wall area,
V_{bldg} = building outside air flow rate (CFM or m^3/s), and
v_{face} = per-unit-area air flow through wall (CFM/ft^2 or m/s), typically 0.04 m/s to 0.08 m/s (4 to 8 cfm/ft^2).

To maximize solar collector efficiency use the higher value of 8 CFM/ft^2; to maximize heat collection, use the lower value of 4 CFM/ft^2.

The resulting size will be the minimum of the area thus calculated and other constraints:

The available unshaded area on the south-facing wall is a constraint.

The size that results in a flow rate of less than 2 cfm/ft^2 also is a constraint, so that some minimal efficiency is maintained.

Energy delivered by the solar ventilation air preheating system and fuel energy saved are calculated by the following equations.

$$Q_{solar} = A_c q_{useful} \times \text{Util} \tag{5-22}$$

$$Q_{saved} = Q_{solar} / \eta_{\ heating} \tag{5-23}$$

Where
Q_{solar} = annual heat delivered by solar ventilation air preheat system (kWh/yr or MBtu/yr),
Q_{saved} = annual fuel energy saved (kWh/yr), and
$\eta_{heating}$ = conventional heating system efficiency.

The fraction "Util", or utilization is the fraction of the total heat delivery of the solar collector that can be used given the operational schedule, heat gain internal to the space, and other factors which may render the preheating of ventilation air undesirable. For example, if a building could use the heat only five of seven days, we would derate the delivery by a factor of $Util = 5/7 = 0.71$ in Equation 5-22. Buildings with high internal heat gain (from lights, computers, people) would have a high mixed-air (fresh air + return air) temperature, and would not be able to use all the heat potentially delivered by a system. A percent utilization of $Util = 0.5$ is a reasonable default value unless more detailed information is available.

Additional fan power required to pull the ventilation air through the solar ventilation preheat system is calculated by the following equation.

$$Q_{fan} = A_c q_{fan} \times (\#hours/day \times \#days/week \times \#weeks/year) \tag{5-24}$$

Where q_{fan} equals the fan power required to pull air through collector, often taken to be 5 W/m^2 (0.5 W/ft^2).

The amount of heat delivered by a solar ventilation preheat system depends on a lot of factors: the solar radiation at the site; the heating degree days at the site; the usage pattern and ventilation rate, the internal heat gain inside the space, and details of the control strategy. These factors are best accounted for in a detailed computer simulation.

But in order to proceed with our simple hand calculation, we present in Figure 5-15 a map of solar ventilation air preheat delivery produced by NREL and also the value of q_{useful} as calculated by monthly equations for locations in the US in Table 5-7 and hundreds of locations worldwide in Table 5-8. The values listed here may be thought of as the maximum heat delivery per unit of solar collector area, and should be reduced by the fraction utilization if a load is not able to use all this heat, such as a building that is closed on weekends or already partially heated by internal heat gain (Figure 5-15 and Tables 5-7 and 5-8).

Assume that the application is heating ventilation air (this data is not for crop drying or other uses that could occur when it is hot out). The key assumption in the calculation of q_{useful} is that the ventilation air temperature delivery is limited to a set temperature, T_{set}, of 26 C (79 F). Notice that there are several cities in warm climates for which the savings listed are zero or very small. This is due to the assumption that heat above this temperature would not be useful for ventilation air. In this application, useful heat delivery is the minimum of the solar energy collected in a day, $q_{solar,day}$, and energy required to heat ventilation air for the day, $q_{load,ventilation,day}$.

$$q_{useful,\ day} = \text{minimum of } (q_{solar,day}) \text{ and } (q_{load,ventilation,day}) \tag{5-25}$$

The solar energy collected in a day is the daily solar insolation incident on a vertical wall facing toward the equator, I_C, multiplied by the system efficiency, η, and the utilization factor.

$$q_{solar,day} = I_c \eta Util \tag{5-26}$$

For industrial process all of this heat might be useful, but for heating ventilation air savings are limited by the room temperature and internal heat gain in the space. Internal heat gain reduces the potential for solar ventilation air preheating systems to save energy. To account for this we subtract internal heat gain from the amount of ventilation load energy that the solar ventilation air preheating system can save.

$$q_{load,ventilation} = v_{face} \rho c_p (T_{set} - T_{ambient,max}) - q_{internal\ gains} \tag{5-27}$$

Where $T_{ambient,max}$ is the daily maximum ambient temperature, which we use because we expect the maximum temperature of the day to coincide with the sunlight. Hours of sun per day, (hours/day) is calculated using the methods of chapter 2. We use the face velocity, v_{face}, of 0.02 m/s (4 CFM/ft^2), and the properties of air at 2 °C (35.5 °F). Most buildings would save less than the value listed in Tables 5-7 and 5-8, and a savings of half this number may be a reasonable expectation (the percent utilization may be on the order of 50 percent). Size of the transpired collector, cost, annual energy delivery, annual cost savings, and payback period may be estimated by this simple hand calculation, but subsequently more detailed analysis using computer tools must be used to refine the estimate of savings.

Example Calculation of Useful Heat Delivery by Monthly Calculation

In this example we calculate the value of annual useful energy delivery, q_{useful}, by taking the minimum of absorbed solar insolation and coincident ventilation air heating load. Savings are estimated on a per-unit-area basis. All the required solar resource and temperature data (I_C, $T_{ambient,max}$, hours/day) are obtained from the NASA Surface Meteorology and Solar Resource data website (NASA 2012) for location latitude 40 and longitude −105 degrees, the location of Denver, Colorado. The face velocity, v_{face}, is 0.02 m/s (4 CFM/ft^2), and the properties of air are taken at 2 °C (35.5 °F). In this calculation we assume all the heat is useful (Util = 1) and we neglect internal heat gain within the space to be ventilated. Table 5-6 lists the environmental conditions (insolation and ambient temperature) and the results of calculating equations 5-25 through 5-27 to estimate the useful heat deliver for each month and for the year.

Thus, even though the available solar energy persists through the summer months, the useful heat delivery is low or zero in summer months because we do not need to heat the ventilation air further. For industrial processes or crop drying, we would not limit the useful heat delivery in this way when estimating savings. In this example, annual useful heat delivery is estimated at 700 kWh/m^2/year. This should be considered a maximum and should be decreased

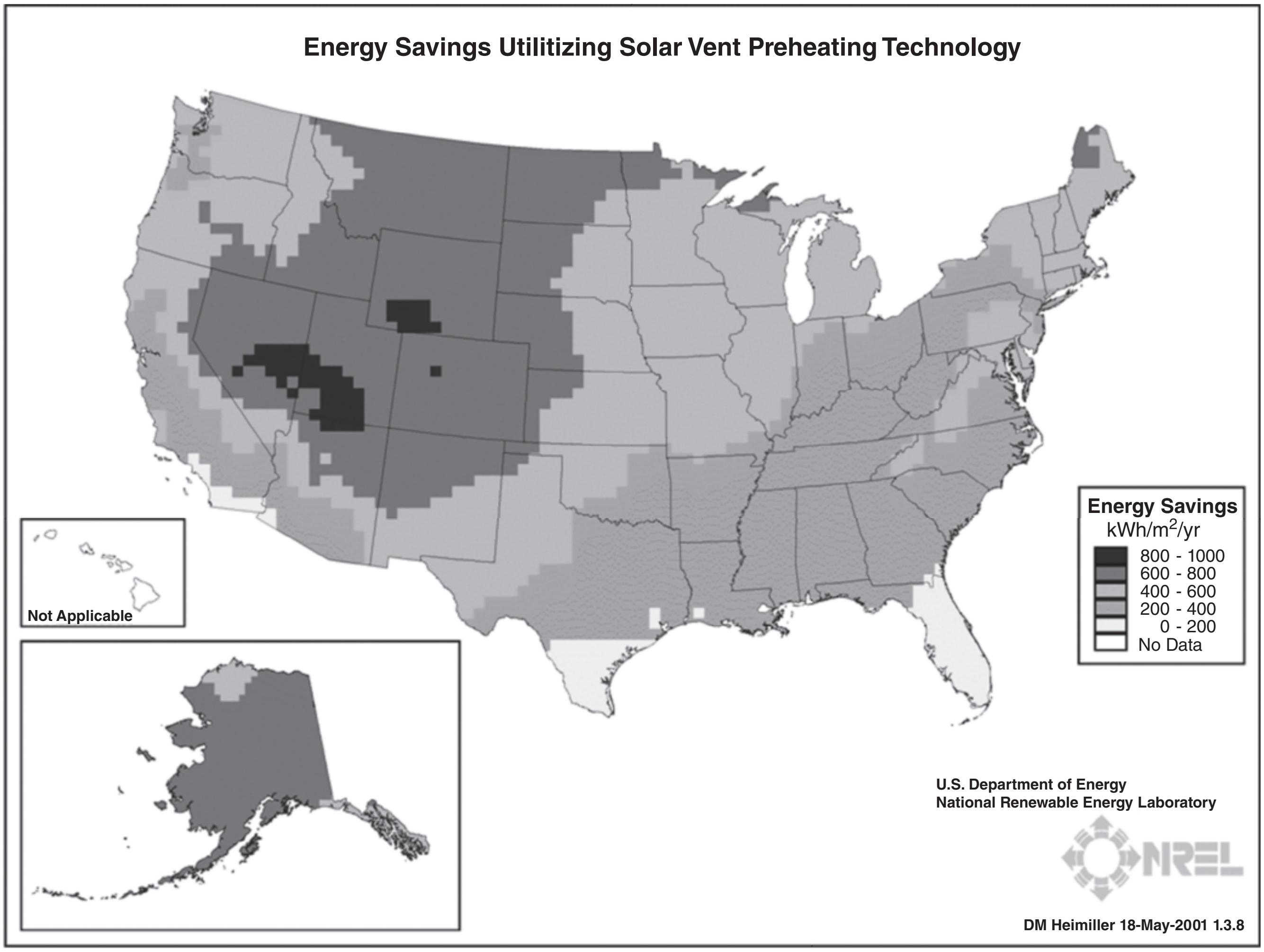


Figure 5-15. Map of estimated annual heat delivery per unit area (q_{useful}), in units of kWh/m^2/year, for the US includes the effect of solar incident on a south-facing wall and heating requirements at each location. This map was created by the National Renewable Energy Laboratory for the US Department of Energy. (Map by Donna Heimiller and Craig Christensen of NREL, courtesy of NREL).

by Utilization and internal gains when estimating savings for a considered project.

Table 5-7 lists the annual results of this monthly calculation of q_{useful} for locations in the US and table 5-8 for locations in other parts of the world. These values may be used in equation 5-22 to estimate the annual heat delivery of a solar ventilation preheat system.

Annual Cost Savings of Solar Ventilation Preheat System

Annual cost savings may be estimated by multiplying annual energy savings by unit cost of energy, and by accounting for the additional fan power imposed by the pressure drop of the solar collector

$$C_{savings} = Q_{saved}c_{fuel} - Q_{fan}c_{electricity} \qquad (5\text{-}28)$$

Where $C_{savings}$ is annual cost savings (\$); C_{fuel} is the unit cost of the electricity or fuel used to heat water and $C_{electricity}$ is the unit cost of electricity consumed by the fan (\$/kWh).

Life-Cycle Cost Analysis of Solar Ventilation Preheat System

Economic analysis and decision making can be complicated, but the simplicity of the situation allows us to consider only two cash flows: the initial cost of purchasing and constructing the solar ventilation air preheating system and the annual savings in operations costs. The net present value of the project may then be approximated by

$$LCC = C_{initial} + C_{savings}\, PWF\,(d,\, N) \qquad (5\text{-}29)$$

TABLE 5-6. EXAMPLE CALCULATION OF q_{useful} ANNUAL ENERGY DELIVERY OF A SOLAR VENTILATION AIR PREHEATING SYSTEM AS A FUNCTION OF MONTHLY AVERAGE CONDITIONS.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Hours/day	9.7	10.7	11.9	13.2	14.3	14.9	14.7	13.7	12.5	11.1	10.0	9.4
I_C	Incident solar on vertical surface facing equator (kW/m^2/day)	3.9	3.9	3.9	3.2	2.8	2.6	2.7	3.0	3.9	4.3	4.0	3.9
$T_{\text{ambient, max}}$	Maximum (daytime) ambient temperature (C)	1.51	3.47	8.3	13	18.7	23.5	26.7	25.2	21	14	5.73	1.09
$q_{\text{solar,day}}$	Solar heat collected per day (kWh/m^2/day) Equation 5-26	2.63	2.65	2.63	2.18	1.88	1.76	1.82	2.06	2.63	2.94	2.73	2.66
$q_{\text{load, ventilation, day}}$	ventilation air heating energy per day (kWh/m^2/day) Equation 5-27	5.95	6.05	5.29	4.31	2.62	0.94	0.00	0.28	1.57	3.34	5.09	5.88
$q_{\text{useful per day}}$	Useful heat collected per day per day (kWh/m^2/day) Equation 5-25	2.63	2.65	2.63	2.18	1.88	0.94	0.00	0.28	1.57	2.94	2.73	2.66
N	Days/month	31	28	31	30	31	30	31	31	30	31	30	31
$q_{\text{useful per month}}$	Sum of $q_{\text{useful per month}}$ (kWh/month)	81.6	74.2	81.6	65.4	58.3	28.0	0.0	8.5	47.0	91.0	81.8	82.4
$q_{\text{useful, annual}}$	Sum of q_{useful} for the year (kWh/m^2/year)	700.2											

TABLE 5-7. MAXIMUM HEAT DELIVERY PER UNIT AREA OF SOLAR VENTILATION AIR PREHEAT SYSTEM FOR CITIES IN THE US, BY STATE. THIS IS THE q_{useful} FOR USE IN EQUATION 5-22.

State	City	q_{useful} (kWh/m^2/year)	State	City	q_{useful} (kWh/m^2/year)	State	City	q_{useful} (kWh/m^2/year)
Alabama	Huntsville	442	Florida	Tampa	325	New York	Buffalo	501
Alaska	Anchorage	570		Orlando	313		New York	438
	Juneau	519		Key West	68	North Carolina	Charlotte	512
Arizona	Chandler	540		Fort Lauderdale	115		Raleigh	525
	Flagstaff	893	Georgia	Atlanta	407		Greensboro	535
	Mesa	565	Hawaii	Honolulu CDP	0	North Dakota	Fargo	615
	Phoenix	453	Idaho	Boise	603	Ohio	Columbus	474

(continued)

TABLE 5-7. (Continued)

State	City	q_{useful} (kWh/ m^2/year)	State	City	q_{useful} (kWh/ m^2/year)	State	City	q_{useful} (kWh/ m^2/year)
	Scottsdale	539	Illinois	Aurora	465	Oklahoma	Oklahoma City	458
	Tucson	497		Joliet	459	Oregon	Portland	553
California	Bakersfield	483		Chicago	493		Salem	610
	Chula Vista	731	Indiana	Fort Wayne	484	Pennsylvania	Philadelphia	465
	Fresno	500	Kansas	Overland Park	492	Rhode Island	Providence	530
	Inyokern	610		Wichita	479	South Carolina	Columbia	478
	Lancaster	545	Kentucky	Lexington-Fayette	477	South Dakota	Sioux Falls	573
	Long Beach	634	Lousiana	Shreveport	420	Tennessee	Memphis	424
	Modesto	467		New Orleans	345	Texas	Amarillo	534
	Ontario	527	Maine	Bangor	612		Arlington	376
	Oxnard	543	Maryland	Baltimore	500		Brownsville	234
	Palmdale	532	Massachusetts	Boston	497		Dallas/Fort Worth	363
	Riverside	584	Michigan	Houghton	579		El Paso	564
	Sacramento	573		Detroit	425		Houston	345
	San Diego	471	Minnesota	Duluth	679		Laredo	265
	San Francisco	654	Mississippi	Natchez	398		Lubbock	495
	Santa Rosa	586	Montana	Billings	610		San Antonio	386
	Stockton	494		Kalispell	736	Utah	Salt Lake City	584
	Truckee	869	Missouri	St. Louis	459		Provo	686
Colorado	Eagle	924	Nebraska	Omaha	551	Vermont	Burlington	602
	Alamosa	971		Lincoln	481	Virginia	Richmond	499
	Denver	700	Nevada	Las Vegas	536		Chesapeake	379
	Fort Collins	727		Reno	725		Norfolk	429
	La Junta	581	New Hampshire	Concord	699	Washington	Yakima	668
Connectiicut	Hartford	549	New Jersey	Newark	432	Washington	Seattle	553
Delaware	Wilmington	478	New Mexico	Albuquerque	677	West Virginia	Huntington	506
Florida	Jacksonville	412		Las Cruces	610	Wisconsin	Madison	593
	Miami	123	New York	Albany	574	Wyoming	Cheyenne	653
							Dubois	828

Source: Created using data from National Renewable Energy Laboratory and the RETScreen computer program, Minister of Natural Resources, Canada www.RETScreen.ca)

TABLE 5-8. MAXIMUM HEAT DELIVERY PER UNIT AREA OF SOLAR VENTILATION AIR PREHEAT SYSTEM FOR CITIES IN VARIOUS COUNTRIES, BY COUNTRY. THIS IS THE q_{useful} FOR USE IN EQUATION 5-22.

Country	City	q_{useful} (kWh/m^2/year)	Country	City	q_{useful} (kWh/m^2/year)	Country	City	q_{useful} (kWh/m^2/year)
Afghanistan	Kabul	708	Congo	Kinshasa	9	Korea, S.	Seoul	485
Albania	Tirana	660						
Algeria	Algiers	473		Lubumbashi	273	Korea, S.	Suwon	694
Angola	Luanda	32	Costa Rica	San José	221	Kyrgyzstan	Osh	645
Argentina	Buenos Aires	488	Côte d'Ivoire	Abidjan	0	Latvia	Riga	441
	Mendoza	556	Cuba	Havana	43	Lebanon	Beirut	371
	Ushuaia	434	Czech Republic	Prague	503	Macedonia	Skopje	581
Australia	Adelaide	614	Denmark	Copenhagen	510	Madagascar	Antananarivo	362
	Alice Springs	474	Egypt	Cairo	205	Malaysia	Kuala Lumpur	0
	Canberra	695	England	Leeds	445	Mali	Bamako	0
Austria	Vienna	499		London	404	Mexico	Chihuahua	540
Azerbaijan	Baku	413	Ethiopia	Addis Ababa	600		Merida	0
Bahamas	Nassau	35	Finland	Helsinki	528		Mexico City	666
Bangladesh	Chittagong	37	France	Marseille	508		Monterey	389
	Dhaka	65		Paris	470	Mongolia	Ulan Bator	901
Belarus	Minsk	503		Lyon	560	Morocco	Casablanca	569
Belgium	Antwerp	516	Georgia	Tbilisi	394	Mozambique	Maputo	90
Belize	San Ignacio	13	Germany	Frankfurt	496	Myanmar	Mandalay	237
Bhutan	Thimphu	804		Hamburg	463		Yangon	0
Bolivia	Santa Cruz	60		Munich	623	Nepal	Kathmandu	797
Bosnia	Sarajevo	671	Iceland	Reykjavik	399	Netherlands	Amsterdam	486
Brazil	Rio de Janiero	82	India	Ahmadabad Gujarat	87	New Zealand	Auckland	268
	Brasília	0		Bangalore	75	Nicaragua	Managua	0
Canada	Edmonton	858		Bhopal	203	Nigeria	Lagos	0
	Montreal	594		Calcutta	132	Norway	Oslo	676
	Saskatoon	852		Chandigarh	486	Pakistan	Faisalabad	356
	Toronto	538		Delhi	332		Gujranwala	433
	Vancouver	577		Dhera Dun Uttaranchal	813		Hyderabad	178
	Winnipeg	696		Gauhati Assam	250		Karachi	178
	Yellowknife	747		Goa	0		Lahore	332
Chile	Punta Arenas	451		Hyderabad	37		Multan	321
	Santiago	463		Itanghar Arunchal	574		Peshawar	364
China	Baotou Niemongol	886		Kargil Kashmir	748		Quetta	557
	Beihai Guangxi	291		Leh Ladakh	777	Paraguay	Asunción	100

(continued)

TABLE 5-8. (Continued)

Country	City	q_{useful} (kWh/ m^2/year)	Country	City	q_{useful} (kWh/ m^2/year)	Country	City	q_{useful} (kWh/ m^2/year)
China (continued)	Beijing	567	India (continued)	Lucknow Uttar	319	Peru	Lima	146
	Changsha Hunan	273		Ludhiana Punjab	400	Philippines	Davao	0
	Chengdu Sichuan	286		Madras	0	Poland	Warsaw	445
	Chungking	213		Manali Himachal	643	Russia	Grozny Chechnya	539
	Fuzhou Fujian	249		Mumbai	0		Moscow	642
	Gangdong Tianjin	622		Patna Bihar	300	Saudi Arabia	Jidda	0
	Ganzhou Jiagxi	332		Pune (Poona)	115	Scotland	Edinburgh	475
	Guiyang, Guizhou	290		Shrinagar Kashmir	472	Senegal	Dakar	132
	Haikou Hainan	181		Trivandrum	0	Somalia	Mogadishu	0
	Harbin Heilongjiang	663	Indonesia	Jakarta	0	South Africa	Cape Town	645
	Hefei Anhui	399		Palembang	0		Pretoria	412
	Hong Kong	188	Iran	Shiraz	491	Spain	Barcelona	212
	Jilin	811		Tabriz	468		Seville	176
	Jinzhou Liaoning	675		Tehran	426	Sweden	Linkoping	595
	Kunming Yunan	605	Iraq	Baghdad	325	Switzerland	Geneva	564
	Lanzhou Gansu	658		Mosul	351	Syria	Aleppo	465
	Lhasa Tibet	981	Ireland	Dublin	418	Taiwan	Taipei	192
	Tsingtao Shandong	369	Israel	Haifa	382	Tajikistan	Dushanbe	597
	Shanghai	343	Italy	Milan	681	Tanzania	Dar es Salaam	0
	Shenzhen Guangdong	219		Palermo	433	Tibet	Lhasa	981
	Shijiazhuang Hebei	701		Venice	459	Tunisia	Sidi Bou Said	348
	Suzhou Jiangsu	410	Japan	Akita	395	Turkey	Antalya	417
	Urumqi Xinjiang	596		Nagasaki	446		Bursa	469
	Wuhan Hubei	299		Sapporo	592		Istanbul	399
	Xian Shanxi	441		Tokyo	467	Uganda	Kampala	329
	Xining Qinghai	888		Yamagata	503	Ukraine	Odessa	455
	Yanchi Ningxia	818	Kazakhstan	Karaganda	740	Venezuela	Caracas	0
	Zhengzhou Henan	491	Kenya	Nairobi	488	Yemen	Sana'a	232
Columbia	Bogota	507	Korea, N.	Pyongyang	665			

Source: Created using data from National Renewable Energy Laboratory and the RETScreen computer program, Minister of Natural Resources, Canada www.RETScreen.ca

Where the present worth factor, PWF, is the factor to discount a stream of annual cashflows down to their present value. For example, the PWF for 25 years of cash flows at 3 percent discount rate is 17.4 years. The PWF has units of years, but it reflects that the value of $1/year for 25 years is only $17.4 today.

Another useful metric is the savings to investment ratio, or SIR, which is the ratio of life-cycle savings to the investment.

$$SIR = \frac{c_{savings} PWF(d,N)}{c_{initial}} \qquad (5\text{-}30)$$

An SIR of greater than one (SIR>1) indicates that a project is cost-effective.

Example Calculations for Size, Cost, and Heat Delivery of Solar Ventilation Preheat Systems

In this example, we consider preheating ventilation air for a building air-handling unit with an outside ventilation air requirement of 0.94 m^3/s (2,000 CFM). The building is located in Denver, Colorado, and ventilation is required only Monday through Friday of the week. The building requires 100 percent outside air, without any recirculation of room air, so a high mixed-air temperature does not reduce the savings in this example. Considering the effect of weekends, we use a utilization fraction of 5/7 = 0. 71. The efficiency of the conventional heating system is taken to be 80 percent. For Denver, Colorado, the value of q_{useful} = 700 kWh/m^2/year from the map by NREL agrees with the maximum heat delivery from the table (and the numerical example of how it is calculated). The additional energy consumption of the fan is based on 5 W/m^2 (0.5 W/ft^2), 9 hours per day, 5 days per week, and 26 weeks per year. For the economic results, we assume a per-unit area cost of $270/$m^2$ ($27/$ft^2$) for the complete solar energy system installation; a price of $0.034/kWh ($1/therm) for fuel; and a price of $0.10/kWh for the electric fan energy.[The results of each of the calculations is listed in Table 5-9. The size of the solar collector is determined by equation 5-12 and then the useful heat delivery, associated fuel savings, and fan power are calculated according to Equations 5-22 through 5-25. Economic results are also presented in the table.

We find that under the set of assumptions and performance data in this example, the solar ventilation preheat system would have a simple payback period of 13 years, which most building owners would consider to be an attractive investment, considering that the system may last over 40 years.

TABLE 5-9. EXAMPLE CALCULATION OF SIZE, ANNUAL ENERGY DELIVERY, COST, AND COST-EFFECTIVENESS OF A SOLAR VENTILATION AIR PREHEATING SYSTEM

Building information			
V_{bldg}	Building ventilation requirement	0.94 m^3/s	2000 CFM
$\eta_{heating}$	Efficiency of conventional heating system	0.8	0.8
Stipulated design values			
v_{face}	Face velocity	0.02 m/s	4.00 CFM/ft^2
% Utilization	Fraction of maximum delivered heat that can be used.	0.71	0.71
From map or table			
Q_{useful}	Heat delivered per unit area of collector From Table 5-7	700 kWh/m^2/year	222 kBtu/ft^2/year
Calculated energy results			
A_c	Area of transpired solar collector Equation 5-21	46 m^2	500 ft^2
Q_{solar}	Solar heat delivery Equation 5-22	23,095 kWh/year	78,999 kBtu/year
$q_{savings}$	Savings in heating fuel Equation 5-23	28,868 kWh/year	97,625 kBtu/year
q_{fan}	Additional fan energy Equation 5-24	272 kWh/year	272 kWh/year
Economic results			
Initial cost	46 m^2 at $270/$m^2$	$12,546	$12,546
Annual cost savings	$0.034/kWh times Qsavings minus $0.10/kWh times Qfan	$949	$949
Simple payback period	Initial cost/annual cost savings	13 years	13 years

COMPUTER TOOLS FOR ANALYSIS OF SOLAR VENTILATION PREHEAT SYSTEMS

A comparison of computer simulation programs is provided based on review of on-line tools directories and involvement or experience of the author. This comparison is not inclusive of all programs available and is not intended to indicate that one is any better than another, but rather that each has appropriate applications. Table 5-10 presents a comparison of the computer programs according to the following criteria:

- Nonproprietary: computer program should be available to competing commercial interests.
- Calculations may be checked: calculations which are used to generate the results should be visible in a spreadsheet form or well described in program documentation.
- Climate data: extensive weather data for multiple countries or access to climate data is facilitated.
- Well tested: computer program validated by comparison to other programs and actual project results.
- Cost: free or low cost.
- User support: contact information is valid and support and training are available.
- Recently updated: program is reflective of current models and computer systems.
- Documentation: complete reference material is available.

A short description is provided for each tool along with other information including expertise required, users, audience, input, output, computer platforms, programming language, strengths, weaknesses, technical contact, and availability.

FRESA

FRESA (Federal Renewable Energy Screening Assistant) provides an early indication if more detailed study of a solar ventilation preheat system is warranted. Life-cycle cost calculations comply with the regulation 10 CFR 436 which Federal agencies use to make economic calculations consistent. Energy delivery is based on a database of savings listed by zip code in the US; for other locations the resource would have to be entered.

- Expertise required: Intended for use by trained auditors; results should be interpreted by someone familiar with the limitations of the program.
- Users: Auditors working under the SAVEnergy Audit Program administered by the Federal Energy Management Program, other web-based users.
- Audience: Building energy auditors.
- Input: Building square footage, number of floors, energy use and cost, ventilation air required, area of available wall area for mounting solar collector, specified face velocity.
- Output: Annual cost and energy savings; life-cycle economics; indicates if a solar ventilation preheating project may be viable; viable options ranked by savings-to-investment ratio.
- Computer platform: Web-based implementation.
- Programming language: C++.
- Strengths: Establishes consistent methodology and reporting format for a large number of audits in varying locations and with varying building use types; sophisticated analyses of technology performance and cost while keeping data requirements to a minimum. Solar and climate resource data provided in a database indexed by ZIP code.
- Weaknesses: Provides only first-order screening, to focus design; requires more detailed feasibility analyses.
- Contact: National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, CO 80401 United States; Website: https://www3.eere.energy.gov/femp/fresa/.
- Cost: Free.

REO

"Renewable Energy Optimization" (REO) is a spreadsheet program to evaluate life-cycle cost of a combination of renewable energy technologies at a site. Data input is facilitated by extraction of resource and incentive data from databases. Uses

TABLE 5-10. COMPARISON OF COMPUTER SOFTWARE PROGRAMS FOR DESIGN OR ANALYSIS OF SOLAR VENTILATION AIR PREHEATING SYSTEM PERFORMANCE

	Nonproprietary	Calculations may be checked	extensive climate data	well tested	Free or Low Cost	User support	Recently updated	Complete documentation
FRESA	*				*			
REO		*		*			*	*
RETScreen	*	*	*	*	*	*	*	*
TRNSYS	*	*		*		*	*	*

a method very similar to the Simple Hand Calculation described above, including the NREL map of savings in the US, to estimate solar ventilation air preheating system performance.

- Expertise Required: Requires training on the data collection and analysis process, familiarity with Microsoft Excel spreadsheet programming.
- Users: Very few. Status is precommercial.
- Audience: Energy project planning consultants
- Input; Site data including floor area each building type (office, warehouse, etc.), utility bill information (energy use and cost), and heating system efficiency. Ventilation rate may be entered or defaults based on building use type. GIS data on renewable energy resources is provided via www.nrel.gov/gis. Incentives data from dsireusa.org; Cost and performance of each RE technology may be edited.
- Output: Suggested transpired collector area, initial cost, thermal energy savings, additional fan energy requirement, utility cost savings and economic outputs such as rate of return and life-cycle cost. All outputs are in Excel and can be copied to MS Word report. A sample of REO spreadsheet output is listed in Table 5-11.
- Computer platform: Windows 2000, XP, Vista
- Programming language: Excel, also uses Premium Solver by Frontline Systems
- Strengths: Efficient processing of site data to identify and prioritize project opportunities.
- Weaknesses: Simple heuristic algorithms. Not full engineering feasibility study.
- Contact: National Renewable Energy Laboratory, 1617 Cole Blvd., Golden CO 80401-3393; E-mail: andy.walker@nrel.gov.
- Cost: Free for government-use license. Available for license to nongovernment companies.

RETScreen

RETScreen provides a module for estimating the energy production and savings, costs, emission reductions, and financial viability for solar ventilation air heating and other types of Renewable-energy and Energy-efficient Technologies (RETs). The software (available in multiple languages) also includes product, project, and climate databases, a detailed user manual, and a training course, including a textbook.

- Expertise required: None, training material included in software.
- Users: >135,000 worldwide in 222 countries.
- Audience: Engineers, architects, technologists, planners, facility managers and educators.
- Input: Floor area of building, area of transpired solar collector, volume of ventilation air required; heating and cooling space set-point temperatures; maximum air delivery temperature, percent use of system per month. Climate data and product data included in software. Default and suggested values for all inputs via manual or project database.
- Output: Energy balance, emission analysis, financial analysis, etc. All outputs are in Excel and can be copied, printed or saved to PDF format.
- Computer platform: Windows 2000, XP, Vista.

TABLE 5-11. EXAMPLE OF RESULTS FROM RENEWABLE ENERGY OPTIMIZATION (REO) SPREADSHEET PROGRAM

	SVP Ventilation Rate (CFM)	**Ventilation Air Heating Load (therms)**	**Solar Vent Preheat Area (ft^2)**	**Fuel Savings (therms)**	**Electric Savings (kWh)**	**Initial Cost ($)**	**Utility Cost Savings ($/year)**
Annual total	10,000	9,567	2,500	3,577	(2,097)	$60,214	$1,632
January		2,395		896	(525)		$427
February		1,794		671	(393)		$340
March		1,185		443	(260)		$245
April		391		146	(86)		$69
May		106		40	(23)		$28
June		0		0	0		$0
July		0		0	0		$0
August		0		0	0		$0
September		52		19	(11)		$9
October		373		140	(82)		$52
November		1,174		439	(257)		$145
December		2,097		784	(460)		$317

- Programming language: Excel, Visual Basic, C#.
- Strengths: Easy completion of feasibility studies for renewable-energy and energy-efficiency technologies.
- Weaknesses: Provides an estimate of energy delivery that is high compared to other estimates due to allowing delivery of air at a temperature higher than space set-point (but lower than maximum delivery temperature).
- Contact: Natural Resources Canada. CANMET Energy Technology Centre—Varennes, 1615 Lionel-Boulet, P.O. Box 4800, Varennes, Quebec J3X 1S6 Canada; Telephone: +1 (450) 652–4621 E-mail: rets@nrcan.gc.ca; Website: www.retscreen.net/. Reproduced with permission of Ministry of Natural Resources, Canada, 2011.
- Cost: Free.

TRNSYS

TRNSYS (TRaNsient SYstem Simulation Program) is a flexible energy simulation program which has been used to model transpired solar collector and system performance. TRNSYS includes a graphical interface, a simulation engine, and a library of components.

- Expertise Required: None to use standard package; FORTRAN knowledge helpful for developing new components.
- Users: Over 500.
- Audience: Engineers, researchers, consulting firms, architects.
- Input: The TRNSYS input file, including building input description, characteristics of system components and manner in which components are interconnected, and separate weather data (supplied with program) are all ASCII files. All input files can be generated by using a graphical user interface known as the Simulation Studio.
- Output: Basic output format is ASCII. The data included in those files can be life cycle costs; monthly summaries; annual results; histograms; plotting of desired variables (by time unit). It is also possible to plot variables online (as the simulation progresses).
- Computer platform: Windows 95 or higher (98, NT, 2000, ME etc.) for TRNSYS interface programs. (Distributed source code will compile and run on any FORTRAN platform.)
- Programming language: FORTRAN (although unnecessary for the use of standard components). It is also possible to write components in C++.
- Strengths: Due to its modular approach, TRNSYS is extremely flexible for modeling a variety of energy systems in differing levels of complexity.
- Weaknesses: Although component models have been prepared by NREL and others, the program is not widely used in the analysis of solar ventilation air systems.
- Contact: Solar Energy Laboratory, University of Wisconsin, 1500 Engineering Drive Madison, Wli 53706; Telephone: (608) 263-1589; E-mail: trnsys@sel.me.wisc.edu; Website: http://sel.me.wisc.edu/trnsys.
- Cost: Version 16, Commercial: $4200, Educational: $2100.

CODES AND STANDARDS RELATED TO SOLAR VENTILATION AIR PREHEATING

There are several local and national codes and standards that relate to air ventilation systems, and the version adopted by local authorities, should be consulted. Building ventilation rates (m^3/s or CFM) are often established according to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 62. *National Electric Code* has requirements such as grounding for electrical components (fan and controls). *International Building Code*, and American Society of Civil Engineers standards regard the building facade such as wind loads (ASCE 7-10, 2010). The Uniform Building Code requirements regarding ordinary ductwork could apply to solar ventilation preheat installations. The stamp of a Professional Engineer licensed to practice engineering in the jurisdiction is generally required for wall structural attachment, ventilation system design, and electrical design. ACGIH (American Conference of Governmental Industrial Hygienists) *Industrial Ventilation; A Manual of Recommended Practice* covers topics essential for industrial ventilation.

Standards regarding transpired solar collector performance include the Canadian Standards Association published ratings of performance factor as specified in CAN/CSA-F378 *Standard for Testing Solar Collectors*. The Solar Rating and Certification Corporation (SRCC) publishes a rating for a type of glazed collector with transpired absorber (the Lubi system described earlier) certified according to SRCC Standard 100-94.

MAINTENANCE OF SOLAR VENTILATION AIR PREHEATING SYSTEMS

The transpired solar collector requires no regularly scheduled maintenance. The fan which draws air through the wall requires lubrication, fan belt adjustment, and fan belt replacement periodically, but the building would have a ventilation fan anyway, so this maintenance is not additional. The wall can be cleaned, but this is not necessary, and it must not be painted as this would plug the tiny air holes. Repair or replacement may be required where the wall is physically damaged, such as by a vehicle or landscape equipment, which would occur with any metal building.

CASE STUDIES OF SOLAR VENTILATION AIR PREHEATING SYSTEM INSTALLATIONS

A solar ventilation preheat system by ATAS International Inc. was installed on a new manufacturing building called the Grant Way Facility in Allentown, Pennsylvania, in October 2006. Shown in Figure 5-16, the 334 m^2 (3,600 ft^2) collector is 6.9 m (22.5 ft) high and faces 16 degrees west of south. The finish is PVDF

Figure 5-16. South elevation for case study of solar ventilation air preheat on a commercial building at Grant Way Facility, Allentown, Pennsylvania, showing transpired solar collector and by-pass dampers. (Photograph courtesy of Dick Bus, ATAS International Inc.).

finish in Classic Bronze color with a solar absorptivity of 0.91. The plenum depth is 23 cm (9 inches) and the total airflow rate is 6.1 m^3/s (13,000 CFM) delivered by two 76 cm (30 inch) diameter fans. The resulting face velocity is 0.018 m^3 of ventilation air per m^2 of collector area (3.6 CFM/ft^2, which is low but in the broad design range of 2 to 8 cfm/ft^2). The layout of the support structure is annotated in Figure 5-17.

Annual energy delivery is measured at 87,925 kWh (300 million Btu/year) of heat. Annual energy cost savings are estimated at \$6,400/year, or \$19.15/m^2 (\$1.78 per ft^2) of collector area. The average temperature rise during daylight hours is 7 C (12.7 F at the 3.6 cfm/ft^2 face velocity). The total cost of \$112,500 includes wall panels and accessories, fans, filters, silencer, all ducting and controls, and averages \$336/m^2 (\$31.25/ft^2). This cost and savings results in a simple payback period of 17 years, but the building owners benefited from a 30 percent federal tax credit, which brought the effective cost down to \$78,750 and the payback period to 12 years. This case-study information is courtesy of ATAS International, Inc. Phone: (800)468–1441, Website: www.atas.com/inspire.

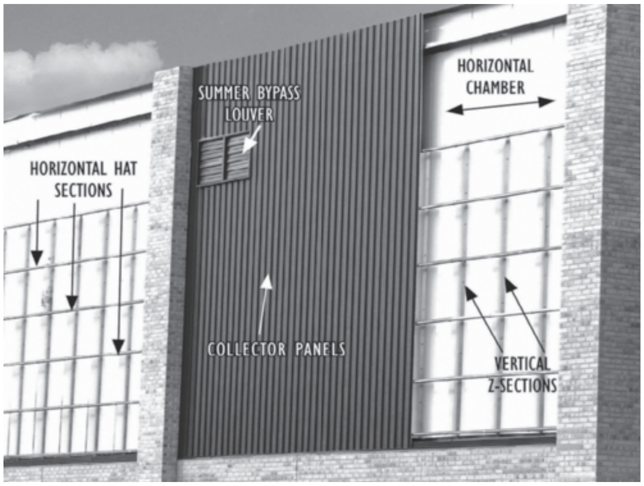


Figure 5-17. Layout of support structure for case study Grant Way Facility, Allentown, Pennsylvania, showing vertical and horizontal air passages through structure. (Figure courtesy of Dick Bus, ATAS International Inc.).

Example

Procurement Specifications for Solar Ventilation Preheat System

These sample specifications are meant to serve as an example and would require modification for any project. This sample is provided courtesy of ATAS International, used with permission. The author has modified these specifications to add language from sample specifications developed by the US DOE Federal Energy Management Program in 2003.

Part 1: General

1.1 Summary

This section specifies the commissioning, design, provision, and installation of a solar ventilation preheat system as described herein and on the associated drawings. The solar ventilation air preheating system includes: transpired solar collector panels, framing to support solar collector panels; flashing and closures; fan(s); ductwork; bypass damper and actuator; structural supports and attachments; instruments and controls; and all appurtenances to make the system complete and operational.

The project location is <building name>, at <address>. Design and installation must satisfy all performance requirements including: ventilation requirements; structural requirements; and thermal performance heat gain requirements. A single contractor shall be responsible for the design, installation, and commissioning of the system.

1.2 Related Documents/Sections

Applicable provisions of fan specifications govern work under this section.

References

- OSHA Standards regarding workplace safety
- The Canadian Standards Association
- The Solar Rating and Certification Corporation
- Metal Construction Association Preformed Metal Wall Guidelines regarding transpired solar collector fabrication and installation.
- SMACNA's "Architectural Sheet Metal Manual."
- Metal Construction Association Technical Bulletin #95–1051.

1.3 Performance Requirements

The solar ventilation preheat system shall be designed to pass and preheat the required amount of ventilation air as listed in the following table.

Air handling unit	**Flow rate of outdoor ventilation Air, lps (CFM)**	**Flow rate of recirculated return air, lps (CFM)**	**Desired ventilation air delivery temperature, C (F).**	**Recirculated return air temperature, C (F).**
AHU-1				
AHU-2				

The solar ventilation preheat system shall be designed to fit within the available south-facing wall areas as listed in the following table.

Wall portion	**Height, m (ft)**	**Width, m (ft)**	**Orientation, (180 = South)**	**Tilt angle (90 = vertical)**
Wall-1				
Wall-2				

System size and design parameters shall be determined based on minimizing life-cycle cost for the building owner. System shall be designed to save as much conventional energy as possible, but within the economic limits of diminishing returns due to overcapacity and low system efficiency.

System shall meet performance requirements of all applicable design loads and observe all applicable codes and standards.

1.4 Submittals

Design: Contractor shall submit complete design drawings and specifications. Submit detailed report showing projected energy savings using RETScreen® solar air heating model, or other recognized calculation techniques. Supplier shall provide calculations estimating the heat delivery capacity of the wall based on test results from independent laboratory for solar collector panels under comparable conditions (sunlight, wind, and ambient air temperature) and at a comparable air flow rate.

Product data: Contractor shall submit the manufacturer's product specification sheet and the manufacturer's installation instructions for all materials to be used. Product literature must be current and representative of the materials used.

Shop drawings: Contractor shall submit, prior to fabrication, shop drawings showing system design, all major components, sequence of operation, all products specified, erection procedures, and accessories required. Drawings shall show details of structural attachments; details of flashing components and other accessories, such as insect screens; details of fastening and anchorage methods of cladding materials and framing. Electronic versions of all drawing submittals shall be included.

Samples: Contractor shall submit, prior to fabrication, samples of actual transpired solar collector material in the profile shape and paint color specified, for architectural selection and/or approval.

Operation and maintenance manual: Contractor shall submit the operation, installation, and maintenance manuals/instructions for all equipment. The complete manual shall provide operating and maintenance instructions for the system as a whole, performance curves, warranty information, approved shop drawings, recommended and complete parts lists, wiring diagrams, and all other bulletins and brochures pertinent to the operation and maintenance of the equipment.

1.5 Quality Assurance

Installer qualifications: a qualified contractor (and subcontractors), licensed as appropriate, and familiar with panel and mechanical/electrical component installation, shall install the solar ventilation preheat system and parts described herein. The system shall be designed by a company experienced with transpired solar collector technology with a minimum of five (5) years of successful history. Manufacturers of mechanical/electrical components shall be ISO 9001 compliant.

1.6 Description of Work

The contractor shall provide complete design and installation, commissioning, and testing for a transpired solar collector of approximately <enter size here> sf in a complete solar ventilation preheat system as described in these documents. The transpired solar collector shall be mounted on the southerly face of <enter building name>.

The solar ventilation preheat system shall include air distribution fan(s) and ductwork, support framing structure and fastening, bypass damper, and controls. System includes balance of system equipment such as disconnects and metering devices as specified and as required to provide a fully functional and operational system.

The work include furnishing and/or paying for all new materials, fee, permits, labor, tools, equipment, transportation, and service required for a complete installation.

1.7 Design

The design shall observe all structural requirements imposed by applicable codes and standards. The solar ventilation preheat system shall be designed to support positive and negative wind loads at a deflection not exceeding 1/180 of the span. Calculations are to be based on the parameters obtained through authorities having jurisdiction or referenced engineering resource: minimum force per area; design wind speed (m/s or mph); wind exposure class; seismic requirements; and any other requirements that must be satisfied to comply with codes and meet all regulatory requirements.

Refer to ASHRAE (American Society of Heating, Refrigerating, and Air Conditioning Engineers) Handbook, Fundamentals for information on air flow around buildings and position the wall where it will not draw in pollution from local sources, such as diesel engines. Do not select wall locations based only on prevailing winds—the transpired solar collector must not suck in pollution under any wind conditions.

Air flow rate, pressure drop across the perforated absorber plate, plate porosity, and distance between fans and intake ducts shall be balanced to achieve a uniform inward flow of air across the wall face, avoiding areas where the flow is stagnant or even outward from the holes. Nonuniform flow across the face of the wall results in diminished efficiency. Design shall maintain at least 25 Pa (0.0026 psi, 0.100 in water column) pressure drop at all points on the face of the transpired collector in order to ensure high efficiency.

1.8 System Operation

The system shall have two operating modes: "on," during which the ventilation air is drawn through the transpired solar collector, and "bypass" during which the ventilation air is drawn through the bypass damper, depending on the controller sequence. The system shall also have an override switch for "off" during which the fan is off. Supplier shall provide a control system with an effective control strategy to maximize useful energy delivery and savings in conventional fuel.

1.9 Delivery and Storage

Protect materials during transport with suitable packaging and handling. Inspect all materials upon delivery. Do not deliver materials until provision for on-site storage and protection are available. Materials shall be delivered to the site in a dry and undamaged condition and unloaded per the manufacturer's instructions. The installer shall inspect materials for damage and stains upon arrival to the site. Materials shall be stored out of contact with the ground in weather-tight coverings to keep them dry per the manufacturer's recommendations. Store materials at a slight slope, so that any water may drain off the surface. Provide painted surfaces protected by a peel-away protective film and protect the film from sunlight. Storage accommodations shall provide good air circulation and protection from surface staining. Do not stack other materials or work on top of the stored metal panels.

Part 2: Products

2.1 General

- All materials and equipment required for the work shall be new and shall be furnished, installed, and finished in every detail, and shall be selected and arranged as to fit properly into the building spaces.
- All electrical equipment shall be listed and labeled per recognized electrical testing laboratory and installed per the listing requirements and the manufacturer's instructions.
- All electrical equipment shall be properly grounded per the requirement of the National Electric Code, Article 250.

2.2 Materials

Metal wall panels: Perforated ribbed panels nominal 1–1/4 inch depth; 26 gauge. Perforations in the metal siding and resulting porosity as required for air flow rate and air balancing requirements.

- Specify transpired collector absorber material: ______ (example aluminum or steel)

(continued)

- Specify material thickness: _____ (example: 0.032 or 0.040 inch aluminum or 22 or 24 gauge steel).
- Specify Profile: _____ Shape (example: Conserval Profile SW200).
- Width: _____ (example 39.4 inch coverage).
- Length: _____ (example: 16 feet or specify longest length available within delivery, handling, expansion, and contraction limits.
- Finish: Manufacturer's standard finish. Finish must be specified to last the service life of the transpired solar collector without repainting.
- Color: Black; provide documentation of the absorption value of the selected color.
- Dissimilar metals: Separate the aluminum panels from direct contact with steel support structure using permanent separation products recommended by the manufacturer or with bituminous coating or rubberized asphalt underlayment in order to stop galvanic corrosion.

2.3 Accessories

Fasteners: Use Type 300 stainless steel or galvanized plated carbon steel #14 x 1 inch TEKS screws, as per design. Galvanized steel fasteners may be used for surfaces exposed only to the interior.

Exposed fasteners: Exposed fasteners shall have a long-lasting, factory, applied color coating to match panels, #14 x 1 inch self-tapping, as per design.

Provide trim, flashing, and accessories from same material as the wall panel system as necessary for a complete installation. Panel lines, breaks and angles are to be formed on equipment designed for that purpose and shall be sharp and straight. Flat surfaces shall be free of noticeable warp and buckle.

Provide bypass louvers to bring in fresh, unheated outside air when the control system indicates that heating of ventilation air is not desirable. Bypass louvers shall have dampers operated by actuators, and the actuators shall be controlled by a thermostat or by the building control system. Configuration of the dampers and fan depend on whether the solar ventilation air system stands alone or preheats for a Heating Ventilation and Air Conditioning (HVAC) system:

1. For systems which introduce the air supply directly into the building, provide a bypass damper unit fully assembled, tested, and complete with intake and return air modulating dampers and automatic discharge air temperature control.
2. For systems in which the air from the transpired solar collector is drawn into a new or preexisting air handling unit (AHU), the first stage of the AHU is to be modified or replaced with a new section which combines the duct from the transpired solar collector, the room air return, and the outside air bypass with bypass damper. System fan shall be sufficient to supply the required air flow rate (cfm) at 1 cm (1/2 inch) water column static pressure.

2.4 Structural Framing

Provide structural framing, subframing, and anchors as a complete system capable of permanently meeting all structural requirements.

- Subgirts: hat-shaped, Z-shaped, or L-shaped.
- Subgirts shall be prefabricated or break-formed from 18 gauge G-90 (Z275) galvanized steel.
- Subgirts shall be located to account for specified wind loading, and existing expansion joints in the building.

2.5 Fabrication

Components shall be fabricated to the greatest extent possible in the factory ready for field assembly.

Part 3: Execution

3.1 Inspection

- Examine the building to verify that the structure is ready for panel installation.
- Move any objects on or in front of wall where solar panels are to be mounted.
- All structural supports shall be in place and connections shall be tightened before work proceeds.
- Prior to ordering materials, field-check dimensions to confirm plans and check alignment of structural supports.

If any condition is found which will prevent proper execution of his work, the installer shall report such condition in writing to the building project manager and shall not proceed until unsatisfactory conditions are corrected. Beginning the installation means that the Contractor has accepted the existing conditions.

3.2 Coordination

The Contractor shall coordinate the installation of the solar ventilation preheat system with the building operation schedule.

The Contractor shall coordinate with the Contracting Officer on the locations and appearance of all exposed equipment, including but not limited to the transpired solar collector, ductwork, fan, and control equipment.

The contractor shall coordinate installation of the transpired solar collector panels, actuated louver dampers, fan power and control, and duct installation for compliance with performance requirements and achieve proper ongoing operation of the system.

3.3 Installation

The Contractor shall perform pullout test to confirm fastener holding strength of fasteners existing building wall prior to installation.

Remove protective plastic film from each solar collector panel immediately prior to installation.

Install metal panels, fasteners, trim, and related items as necessary for a complete installation. Install transpired solar collector panels of the sizes specified and in the orientation and location indicated on the drawings. Install transpired solar collector panels, supports, flashing, and related components in accordance with manufacturer's instructions. Install panels with the profile ribs running perpendicular to girts and subgirts, unless otherwise indicated. Anchor transpired solar collector panels, flashing, and other components securely in place with accommodation for thermal expansion and contraction as well as structural movement of the building.

Rigidly fasten lower end of transpired solar collector panels and allow top end to move to accommodate thermal expansion and contraction. Splice collector panels together at the location of structural supports. Lap upper panels over lower panels to shed water. Stagger the horizontal lap joints and the vertical splice joints so that four joints do not come together in a corner. Install gaskets, joint fillers, and sealants where indicated.

Provide weatherproof escutcheons for any pipe or conduit penetrations through the wall.

Protect installed panels from damage abuse by other trades or subcontractors.

Protect the panels from wet cement, plaster, painting operations, etc.

Install screw fasteners. Predrill holes for screws in the material if required. Attach panels using manufacturer's standard clips and fasteners, aligned, level, and plumb, within specified tolerances.

Installation tolerances: Shim and align panel units within installed tolerance of one-quarter inch in 20 feet on level/plumb/slope and location/line as indicated and within 1/8-inch offset of adjoining faces and of alignment of matching profiles.

Field cutting of metal wall panels by torch or saw is not permitted.

3.4 Damaged Material and Cleaning

Touch-up minor abrasions with matching touch-up paint provided by the solar collector manufacturer. Replace damaged solar collector panels and other components of work which cannot be repaired by finish touch-up or similar minor repair.

To prevent rust staining, immediately remove from finished surfaces filings caused by drilling and cutting.

Wipe down each area after erection is complete. Sweep and remove chips, shavings, and dust from work area on a continuous basis during installation and remove scraps and debris from site following installation. Leave solar collectors and flashing clean, free from grease, finger marks, and stains.

3.5 Commissioning

The contractor shall provide complete testing and commissioning of the solar ventilation air preheating system.

Verify that all equipment is installed and connected correctly and in accordance with manufacturer's written instructions.

- Perform startup checks for all equipment per manufacturer's written instructions.
- Replace all damaged and/or malfunctioning equipment.
- Provide written report on system performance.
- Demonstration and training
- Provide a complete walk-through and training service for the solar ventilation preheat system. Provide operation and maintenance manuals to owner for review and approval ______ weeks prior to walk-through. Provide as-built drawings at walk-through.
- Train maintenance personnel on procedures and schedules for starting and stopping, troubleshooting, servicing, and maintaining equipment. Describe operation modes and safety precautions.

3.6 Warranty

- Provide 30-year finish warranty for color retention, adhesion, and freedom from chalking.
- Provide 10-year warranty for fan.
- Provide 1-year warranty for controls and damper actuators.

Part 4 Fan Specifications

4.1 Description

Configuration of the fan system depends on whether the solar ventilation air system stands alone or preheats for a Heating Ventilation and Air Conditioning (HVAC) system:

1. For systems which introduce the air supply directly into the building, provide a fully assembled fan unit, tested and complete with electric motor and intake and return air modulating dampers and automatic discharge air temperature control.
2. For systems in which the air from the transpired solar collector is drawn into a new or preexisting HVAC air handling unit (AHU), the AHU fan is to be specified at the required air flow rate (cfm) at 1 cm (1/2 inch) water column static pressure.

The air make-up units shall be fully assembled, tested, and complete with intake and return air modulating dampers and automatic discharge air temperature control.

Each unit shall have a capacity of ______ CFM at ______" static pressure, complete with ______ HP totally enclosed motor and bearings designed for continuous operation, ______ Volts, 3 Phase, 60 Hertz.

4.2 Fan Housing

The exterior fan housing shall be constructed of heavy gauge galvanized steel. Two access panels shall be supplied providing access to fan cabinet.

(continued)

4.3 Dampers

The fan unit shall have intake and return air dampers, interlinked, and powered by a modulating actuator. Intake dampers shall automatically close when fan is not operating or when power is turned off.

4.4 Wiring

Fan unit shall be shipped with all internal wiring completed and a terminal strip within control cabinet labeled for field connection.

4.5 Control Section

The fan control section shall include a factory mounted and wired proportional temperature controller to automatically control discharge air temperature and modulate intake and return air dampers. Control shall be mounted in control cabinet on fan and temperature sensor shall be mounted in mixed-air stream.

4.6 Option

Proportional electronic remote temperature controller, mounted in lockable metal enclosure for easy field installation at floor level, to automatically control discharge air temperature and modulate intake and return air dampers.

4.7 Distribution Ducting

Distribution ducting may be flexible ducting suspended in space or rigid ducting. Ducts may deliver ventilation air directly to the space or may deliver air to the outdoor air intake of the air handling unit. Distribution ducting shall be flexible ducting, 42 inch diameter, with mounting grommets located on top of duct complete with mounting hooks. Duct to be perforated with 2½-inch-diameter holes at 2 o'clock and 10 o'clock and to have a discharge air velocity of 2,000 ft/min. Ducting to be fabricated of high density polyethylene, 12 mils thick, two sides flame retardant coated, to meet self-extinguishing requirements of Specification CPA1 84 Section 6 and 7; UL Listed; NFPA #701 Small Scale Test.

Duct support cable and related hardware shall be supplied for support of distribution ducting.

4.8 Warranty

The fan unit shall bear a manufacturer's warranty against defects in material and workmanship for a period of one year from date of installation.

REFERENCES

ATAS. 2011. "Inspire Product Info." www.atas.com/Products/Wall/Solar/InSpireWall/tabid/110/Default.aspx (accessed August 28, 2011).

Barker, G., K. Kiatreungwattana. 2011. Pressure Drop as a Function of Air Flow Rate for Roll-Punched Transpired Solar Collectors With Different Porosities. ASME Energy Sustainability Conference 2011. Washington, DC: American Society of Mechanical Engineers.

CSA International. 2011. "CSA International Certified Product Listing." CSA International: directories.csa-international.org/directorymain.asp (accessed September 20).

Dymond, C., and C. Kutscher. 1997. "Development of a Flow Distribution and Design Model for Transpired Solar Collectors." *Solar Energy* 60: 291–300.

Ehrlich, B. 2011. "Alex's Cool Product of the Week." BuildingGreen.com. http://greenspec.buildinggreen.com/blogs/transpired-solar-collector-performance-more-hot-air (accessed July 1, 2011).

Incropera, F., and D. DeWitt. 2005. *Fundamentals of Heat and Mass Transfer*. 7th ed. New York: John Wiley and Sons.

Kutscher, C. 1994. "Heat Exchange Effectiveness and Pressure Drop for Air Flow Through Perforated Plates with and without Cross Wind." *Journal of Heat Transfer*, 116: 391–99.

Kutscher, C., C. Christensen, and G. Barker. 1993. "Unglazed Transpired Solar Collectors: Heat Loss Theory." *Journal of Solar Energy Engineering* 115:182–88.

Moaveni. Saeed. 2011. "A Numerical Model for Thermal Performance of an Unglazed Transpired Solar Collector". Energy Sustainability Conference 2011. Washington, DC: American Society of Mechanical Engineers.

NASA. 2012. "NASA Surface Meteorology and Solar Energy-Available Tables." eosweb.larc.nasa.gov. ://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?&num=076131&lat=40&submit=Submit&hgt=100&veg=17&sitelev=&email=andy@ambient-e.com&step=2&p=grid_id&p=daylight&p=ret_tlt0&p=T10M&lon=-105 (accessed March 9, 2012).

6

Solar Space Heating and Cooling

A quote attributed to Socrates explains passive solar heating: "In houses that look to the south, the sun penetrates the portico in winter, while in summer the path of the sun is right over our heads and above the roof so that there is shade" (Butti and Perlin 1980). People have understood passive solar for thousands of years, but designs described in this chapter are made possible only by much more recent advances in the performance of windows, insulation, and thermal storage systems. Solutions become technically feasible only if heat loss is limited to an amount that can be provided and stored within the building itself by solar.

First-century Roman glassblowers made glass window panes by blowing air into a ball of molten glass, swinging it into a cylinder, and then cutting and unrolling it into a flat sheet. But it was not until 1935 that Libbey Owens Ford introduced sealed, insulated glazing and only very recently that triple-pane windows, and even quadruple-pane windows, with optical coatings, suspended films, and filled with low-conductivity gas, have been broadly available and affordable. Similarly, technical advances make insulation more effective against heat loss and air infiltration, inexpensive, easy to install, fire-retardant, resistant to pests, and able to retain these properties over time. Computer programs and sources of climate data for design and analysis have evolved so that energy modeling is more affordable and provides results early enough in the design process to inform decisions. Finally, sophisticated phase-change storage is probably required to store enough heat to balance the heating load within a tolerable temperature range (Walker et al. 2003).

Doug Balcomb at NREL pioneered early calculation methods for passive solar. He applied an "R-C circuit" model in which heat flow was analogous to electric current, the R-value of the room was analogous to electric resistance and the specific heat of mass in the room was analogous to an electric capacitor. Before computers were everywhere he produced a series of location-specific guides called *Passive Solar Design Strategies* (PSIC 1995), which included worksheets to calculate glazing and mass sizes. After computers became widely available he produced the Energy10 software which was a huge step forward toward "whole-building" design. Energy10 allowed a designer to get results very early in design because the program was loaded with default values that could be changed at different levels of detail as the design evolves.

The experts at Steven Winter Associates have also contributed a lot to the field of passive solar heating and whole-house design. Steven Winter published *The Passive Solar Design and Construction Handbook* (Steven Winter Assoc. 1998), which presents details of how to construct window and mass wall assemblies, and was also a founding force behind the Passive Solar Industries Council, now the Sustainable Buildings Industry Council. Other people who have contributed a lot to the development of solar buildings include architects Ed Mazria in Santa Fe New Mexico and Greg Franta in Boulder Colorado.

Passive solar solutions are not "one size fits all." Not all buildings can even benefit from passive solar heat. For example, if a building has a lot of internal heat sources such as computers, then solar heat is rarely welcome. Still, all buildings are affected by solar heat through windows and roofs, so good building design would accentuate positive aspects of solar heat gain and prevent unwanted aspects of it.

Usually, we don't have the luxury of choosing the land for the building we are designing, but at least some solar exposure is required for a solar building. The south-facing slope of a hill is ideal. However, even in urban environments with tall buildings, some wall and roof surfaces will probably get some sun for a least a few hours a day—and we base the size and type of solar system on those exposed surfaces.

SITE ISSUES

There are several site and building considerations affecting the passive solar aspects of the building design:

Aspect ratio: This is the ratio of the length of a room to its width. A square floor plate minimizes surface area, which minimizes heat loss, but direct solar heat can only be expected to penetrate about 15 feet into a room and daylight penetrate about 20 feet. Frank Lloyd Wright said a floor plate should not exceed 44 feet from the south side to the north side for good daylight and natural ventilation. The building I work in has a 60 feet floor plate, and it has a good distribution of daylight, but it has special reflectors to bounce sunlight deeper into the space.

Articulation: Although a cube-shape minimizes surface area, some degree of articulation is required in the design to ensure that each room has access to solar heat gain, daylighting and natural ventilation. Off-setting rooms horizontally creates some south wall area in each room; off-setting rooms vertically exposes a south vertical wall area for a clerestory window—admitting direct sunlight into rooms on the north side of the building. A courtyard also allows sunlight to be incident on the south side of a north-room wall.

Orientation: In the Northern Hemisphere, solar heat is a maximum on the south vertical wall of a building in the winter, when the sun follows a low arc across the southern sky; and it is maximum on east wall, roof, and west-facing wall in the summer, when the sun passes almost directly overhead. Thus to stretch the long axis in an east-west direction maximizes solar exposure in winter and minimizes it in summer. A door on the north side will be subject to accumulation of ice. Even in historic neighborhoods doors are on the south, east and west sides so that they get at least some sun each day. Windows should be on the south side of the room, and on the north side to the extent that they are needed to achieve daylighting goals. In the Southern Hemisphere these directions are reversed. Windows for passive solar heating should be on the side facing the equator.

Plantings: Trees on the south side, or the side facing the equator, block sunlight coming into a single-story building's passive solar features, so should be avoided. Deciduous trees, which are just growing their leaves in spring but fully vegetated in autumn, are ideal on the east and west sides. Evergreens trees help block wind on the side facing north, or toward the pole.

Surface properties: Exterior to the building, if the wall facing toward the equator were a dark color, it would absorb winter sun, while a white or light color would reflect summer sun from the flat roof and east and west walls. If the horizontal surface, such as a patio, in front of windows is a light surface, it will help by reflecting more light into the window. Interior to the building mass surfaces upon which we seek to absorb solar radiation would be a dark color, while other, lightweight surfaces such as drywall would be a light color to reflect solar heat to the mass and to distribute daylight.

BUILDING HEAT LOSS

The rate at which a room loses heat (watts) to the ambient is

$$q_{\text{loss}} = (UA)(T_{\text{room}} - T_{\text{ambient}}) \tag{6-1}$$

(UA) in Watts/C, is the heat loss coefficient, U (W/m^2/C), of the room materials per unit area of surface area to the ambient and per degree of temperature elevation above ambient temperature; multiplied by A (m^2), the effective surface area of the room. The temperature difference driving the heat flow is the difference between the room temperature T_{room} and the ambient temperature, T_{ambient}.

Integrated over time the cumulative heat loss Q_{loss} may be expressed as

$$Q_{\text{loss}} = \int q_{\text{loss}}\, dt = (UA)HDD \tag{6-2}$$

Where

$$HDD = \int (T_{\text{room}} - T_{\text{ambient}})\, dt \tag{6-3}$$

Here we consider this integral of heating degree days for the coldest month of the year, usually January, in the Northern Hemisphere, and calculate the average value of ΔT in units C days/days = C.

$$\Delta T = \frac{HDD_{\text{month}}}{\left(\dfrac{31\text{days}}{\text{month}}\right)} \tag{6-4}$$

The overall (UA) of the room is determined by adding up the heat loss from all the wall elements of the room and including a term for the infiltration of ambient air into the structure. Notice that mc_p also has units of watts/C.

$$(UA) = \sum U_i A_i + m_{\text{infiltration}} C_p \tag{6-5}$$

Where U_i is the thermal heat loss coefficient of each building element (roof, wall, floor, window, door, etc.) in W/m^2/C and A_i is the surface area of that element in m^2. The U-value of an element may be calculated from its thermal conductivity, k (W/m/C) and its thickness, t (m). In IP units the U-value would have units of btu/hr/ft^2/F.

$$U_i = \frac{k}{t} \tag{6-6}$$

The mass flow rate of the infiltration air, $m_{\text{infiltration}}$, is difficult to predict accurately, but models exist based on the height of the building, the indoor/outdoor temperature difference, and the ambient wind speed. Mass flow rate m is density ρ times volume flow rate and density is typically 1.2475 kg/m^3 (0.078 lbm/ft^3). Specific heat of air is around $c_p = 1.00$ kJ/kgK (240.4 Btu/lbmF) for the temperatures considered here. Humidity difference between indoor and outdoor air may also be involved in the calculation of infiltration heat loss (Walker 1998; 2008). Here we assume 0.4 "air-changes per hour," which is about as low as you would want without providing mechanical ventilation. Air changes per hour is the volume flow rate of the air (m^3/hour) divided by the volume of the room in m^3.

The heat required is the heat loss reduced by internal heat gain from busy people and computers and lights within the space.

$$P_{\text{heat}} = [(UA)(T_{\text{room}} - T_{\text{ambient}}) - P_{\text{internal}}] \tag{6-7}$$

Over the course of a day, the heating energy required is

$$E_{\text{heat,day}} = \int_{\text{day}} [(UA)(T_{\text{room}} - T_{\text{ambient}}) - P_{\text{internal}}]\,dt \tag{6-8}$$

And the fuel consumed by the heater in providing this much energy without any solar input would be

$$E_{\text{fuel}} = \frac{E_{\text{heat}}}{\eta_{\text{heater}}} \tag{6-9}$$

Where η_{heater} is the efficiency of the heater and may be 1.0 for electric resistance baseboard or fan-coil unit but may be more than 1.0 for a heat pump and may be less than 1.0 for a natural gas, propane, oil, or solid-fuel boiler or furnace. Natural gas boilers range from 0.8 to 0.94 efficiency and furnaces from 0.8 to 0.97. The higher efficiency numbers refer to "condensing" heaters which cool the exhaust produced by combustion lower than the dew point of the water vapor in the exhaust. The water vapor comes from the hydrogen in the hydrocarbon fuel combining with oxygen during combustion. Condensing the water vapor in the exhaust improves efficiency by about 10 percent.

SOLAR HEAT GAIN THROUGH WINDOWS AND OPAQUE SURFACES

The solar heat gain through a window is proportional to the solar heat gain coefficient (SHGC), which is the fraction of the incident solar heat getting through the window to the inside of the room, including both direct beams of sunlight coming through and heat absorbed in the glass that eventually makes it into the room. This is a property of the glazing assembly which is stamped on the label of every window. The solar heat gain (power, in units of W or kW) is

$$P_{\text{solar}} = A_c K I_c SHGC \tag{6-10}$$

Where K is the incident angle modifier previously provided as Equation 3-21 with respect to solar collectors. The energy coming through a window over the course of day would be

$$E_{\text{solar,day}} = \int_{\text{day}} A_c K I_c SHGC\,dt = A_c K\, I_{c,\text{day}} SHGC \tag{6-11}$$

Where $I_{c,\text{day}}$ equals the total solar insolation incident on the window over the day, usually on the order of 3 kWh/m^2/day for a south-facing vertical window, and will be tabulated in Table 3-10 below for many locations in the United States and also for many international locations. If the sunlight is incident on opaque exterior surface the heat gain on that surface is

$$P_{\text{solar}} = A_c K I_c \alpha \tag{6-12}$$

Where α is the solar absorptivity of the surface. The window makes an effective trap of the radiation, but most of the heat absorbed by an opaque surface will be lost to the ambient air. Still, by causing the surface to be at a much higher temperature, solar energy incident on opaque surfaces of a building, especially large horizontal roof areas, contribute to the cooling energy requirements of a building. Thus for the flat roof of a building, it is desirable to specify a white roof with a low solar absorptivity, α. For example, a black asphalt roof absorbs perhaps 90 percent of the incident solar heat, whereas a white thermoplastic vinyl absorbs only 20 percent and reflects 80 percent.

The best way to calculate cooling savings associated with a cool roof, or white roof, is with an hourly computer simulation. But we can get a rough estimate with a simple hand calculation. The first law of thermodynamics (conservation of energy) applied to the surface of the roof gives

$$A_c K I_c \alpha - hA(T_{\text{surface}} - T_{\text{ambient}}) - \frac{A}{R(T_{\text{surface}} - T_{\text{room}})} = 0 \tag{6-13}$$

Where h is the convective heat loss coefficient to the ambient air and R is the R-value of the insulation under the roof. Considering the difference in this equation with different values of α, the different surface temperature may be calculated

$$T_{\text{surface with } \alpha_1} - T_{\text{surface with } \alpha_2} = \frac{I_c(\alpha_1 - \alpha_2)}{\left(h + \frac{1}{R}\right)} \tag{6-14}$$

and the difference in heat transferred to the space that has to be removed by the air conditioning load would be

$$P_{\text{savigns}} = \frac{A_{\text{roof}} I_c (\alpha_1 - \alpha_2)}{R\left(h + \frac{1}{R}\right)} \tag{6-15}$$

Where P_{savings} (watts) is the reduction in the rate of solar heat transferred into the cooled space through the roof insulation R-value (m^2C/W, $hrft^2F/Btu$) in going from a dark roof of α_1 to a lighter roof of $\alpha_{2.}$

To get the savings in energy consumed by the air conditioning system to remove this much heat, we divide by the "coefficient of performance" (COP) of the air conditioning the system. The COP is a measure of how many units of heat energy the air conditioner removes from the space per unit of electric energy consumed. With the exception of h all the other terms are essentially constant, so if we want the energy savings over a day, $E_{\text{savings,day,}}$ we can substitute the instantaneous $I_{c,\beta=0,}$(kW/m^2) with an integrated value $I_{c,\beta=0,\text{day}}$ (kWh/m^2/day).

Example Calculation of Savings due to a Reflective Roof

Estimate how much air conditioning energy could be saved per summer day if the roof of a building in Key West, Florida, were to be specified with a white color and low solar absorptivity of 0.2 rather than a black surface with a high absorptivity of 0.8. The roof is 1,000 m^2 (10,760 ft^2) area and insulated to R = 2.5 m^2C/W (20 ft^2Fhr/Btu), and the convective heat transfer coefficient off the top of the roof is 12 W/m^2C (2.1 $Btu/ft^2/hr/F$). The COP of the air conditioning system is 3.0. Assume the building has a lot of internal heat gain and is always cooling.

From Table 6-10 presenting solar data for many locations later in this chapter, we find that for Key West, Florida, the daily solar insolation on a horizontal surface averaged over the month with the most cooling degree days is $I_{c,\beta=0,\text{day}} = 6.2$ kWh/m^2/day. Table 6-1 lists these inputs and the results of equations 6-14 and 6-15 to calculate daily heating energy savings as a result of the white roof, which is a type of passive solar energy system.

Selection of a white roof instead of a black one would in this example save around 28 kWh of electricity otherwise used to run the air conditioner on a single summer day.

MATERIALS AND BUILDING COMPONENTS FOR PASSIVE SOLAR SPACE HEATING SYSTEMS

We have already discussed solar water and air heating system components of the type that would be used in active space heating systems in chapter 4. We've already discussed the components of a photovoltaic system in chapter 3, and PV could provide energy to run a heat pump for space heating or cooling.

TABLE 6-1. EXAMPLE CALCULATION OF COOLING SAVINGS RESULTING FROM A REFLECTIVE ROOF SURFACE

Roof Properties

A_{roof}	**Surface area of building roof**	**1,000 m^2**	**10,760 ft^2**
α_1	solar absorbivity of black roof	0.8	
α_2	solar absorbivity of cool roof	0.2	
R	Roof R-value	3.5 m^2C/W	20 ft^2hrF/Btu
h	convective heat transfer coefficient from wind on roof	12 W/m^2C	2.1 Btu/ft^2hrF
COP	Coefficient of performance (efficiency) of air conditioner	3	

Ambient conditions

$I_{c,\beta=0,\text{ day}}$	Daily solar insolation on the horizontal averaged for the month with the highest CDD Table 6-10	6.1 kWh/m^2/day	

Calculations

T_(surface with α_1) – T_(surface with α_2)	difference between roof surface temperature with black or white roof Equation 6-14	48.8 C	87.9 F
$E_{\text{savings, day}}$	Daily energy savings of white roof = (A_{roof} $I_{c,\beta=0,\text{day}}$ ($\alpha_1 - \alpha_2$)/(R(h + 1/R)))/COP Equation 6-15	28.2 kWh/day	96,205 Btu/day

We've already discussed solar ventilation air preheating in chapter 5, which can contribute to space heating by delivering an air temperature in excess of the desired room air temperature. Here in this chapter we consider some of the details of building components that make up passive solar heating system: insulation; windows; and thermal storage.

Insulation

Superior insulation comes first in this discussion because it is essential for passive solar design. While it is possible to heat a leaky building envelope with a wasteful supply of fossil fuel, it is technically not feasible to provide that much heat with solar systems built into the architecture. But it is feasible to provide a large fraction, if not all, of the heat that a building needs with solar if the envelope is very well insulated, and the required amount of heat is drastically reduced. This relates to the properties of the insulation, the amount of insulation installed, and the integrity of the installation.

Materials with very low thermal conductivity, k, have been engineered, but the most important thing is that the insulation be continuous without gaps. R-value appears in the denominator of the heat loss calculation, so if insulation is absent there can be a lot of heat lost through even a very small area. Spray foam insulation seals around all the framing members, helping ensure that all surface area is insulated.

Insulating concrete forms are available that are polystyrene foam in the shape of interlocking blocks or separate panels connected with ties. Structural insulated panels (SIP) are polystyrene insulation between sheets of oriented strand board. With insulation in the form of batts or boards, the insulation should fit the cavity precisely and any small gaps should be stuffed with insulation. An exterior insulation and finish system (EIFS) places continuous board insulation on the outside of the wall structure, avoiding gaps and thermal bridging through the framing, as well as encapsulating the mass of the structure for use as thermal storage.

Most passive solar design books recommend moving insulation over windows at night, but I have yet to find a movable insulation product that I would recommend. The ones I've tried have been somewhat expensive and bulky in the room, and have required a lot of attention from occupants to use correctly. Thus I stress the importance of well-insulated window glass used with ordinary drapes and blinds.

Windows

Technological improvements in window properties make passive solar design possible. The well-insulated windows available today allow for large window areas even in cold climates. Without such low U-values, heat loss from expansive glazing is excessive. U-value may be reduced by a "low-e" coating, which reduces the emissivity (and thus the radiant heat loss) off the outboard side of the inner pane. This may be a sputtered "soft coating" of semiconductor such as Ag/TiO$_2$ or a baked "hard coating" such as SnO$_2$. U-value is also reduced by adding a third pane of glass or film to reduce heat loss. Figure 6-1 shows a triple pane window. The thickness of the gap is on the order of the thickness of the "boundary layer" so that viscosity overcomes convection. Conduction heat loss is reduced by a heavy gas, such as argon, that has a low thermal conductivity (Walker et al. 2003).

Definition

The definition of R-Value

The "R-value" of a building element is the inverse of the "U-value," that is, $R = 1/U$. "R" stands for "resistance" to heat transfer and thus has units of m^{2}C/W or hrft^{2}F/Btu. The R-value of several common types of insulation used in buildings is listed in Table 6-2 (RS Means 2011).

TABLE 6.2. THERMAL RESISTANCE TO HEAT LOSS (R-VALUE) OF SEVERAL COMMON INSULATING MATERIALS

Material	R-value (m^{2}C/W) per inch	R-value (hrft^{2}F/Btu) per inch
Fiberglass	0.7	4.0
Cellulose, loose fill	0.65	3.7
Cotton, batt	0.59	3.4
Polyurethane, spray	1.1	6.2
Icyneen, spray	0.76	4.3
Polystyrene, board	0.87	5.0
Polyisocyanurate, board	1.32	7.5
Polystyrene Insulated concrete forms	3 to 4.6 m^{2}C/W for wall	17 to 26 hr ft^{2}F/Btu for wall

Source: RS Means 2011

Solar heat gain may be reduced by a reflective coating on the outside of the glass, and this might result in a silver or gold metallic appearance. A tint may be added which results in a green, blue, or bronze appearance. If a clear appearance is desired a "selective" glass with a sputtered semiconductor coating (similar to a low-e coating) that absorbs the infrared portion of the solar spectrum and lets the visible part of the spectrum

Figure 6-1. Windows with a very low U-value, like this triple pane window, are required to get the heat loss from a space down to a level that it may be maintained by solar heat. (Photo by the author)

Figure 6-2. The electrochromic glass in these west-facing windows is shown just beginning its transition from clear to tinted state. The change occurs starting in the electrode visible at the center of each pane, once the transition is complete, the appearance is uniform. (Photo by the author)

pass. The band gap of the semiconductor material used for the coating corresponds to the wavelengths of light to be absorbed. The energy of sunlight is 48 percent in the visible range, 6 percent in the ultraviolet, and 46 percent in the infrared portions of the spectrum, and by screening out the ultraviolet and infrared, selective glass achieves a visible transmittance 50 percent more than its solar heat gain coefficient. Most windows have a coating to absorb ultraviolet light to UV avoid damage to materials inside a building.

Vertical glazing facing toward the equator (facing south in the Northern Hemisphere) is often recommended, although facing the windows to point east of south delivers the heat earlier in the cold morning, which is better than later in the warm afternoon.

Windows have been developed that are capable of changing their properties to suite the conditions. For example, when a room is overheating its SHGC may be reduced or if privacy is desired the visible transmittance may be reduced. Such types of windows include:

Electrochromic: changes transmissivity (SHGC and τ_{visible}) in response to an applied low electrical voltage. The voltage causes a migration of ions into and out of an electrochromic layer, changing it's properties. Figure 6-2 shows electrochromic windows.

Thermochromic: changes transmissivity in response to window surface temperature. Figure 6-3 shows thermochromic windows.

Photochromic: changes transmissivity in response to the intensity of light hitting the glass.

The windows are one of many components (walls, doors, etc.) that have a U-value for the heat loss calculation. Window U-value is a property of the window assembly and is included in the information on the label affixed to every new window (NFRC 2005). Other window properties include solar heat gain coefficient (SHGC) and visible transmittance.

In addition to glass, fiber-reinforced plastic and plastic glazing products with a wide range of honeycomb cross-sections are available. Despite their low cost and simple mounting, these materials can have properties very favorable for solar applications in greenhouses, homes and commercial construction.

Figure 6-3. The thermochromic glass in these east-facing windows change their transmissivity in response to a change in temperature. The appearance during transition from clear to tinted state is due to temperature differences. Once the transition is complete the appearance is uniform.(Photograph by the author)

Definition

Window Properties: U-value, SHGC, and $\tau_{visible}$

Properties of a window (see Table 6-3) are listed in the manufacturer's literature and also on the label affixed to each window. Properties are certified by the National Fenestration Rating Council (NFRC 2005) and include:

Heat loss coefficient—U-value (ft^2Fhr/Btu)—is the heat loss rate per degree temperature difference between inside and outside of the window and per unit area of window. The U-value often includes the glazing and the frame together.

Solar heat gain coefficient, SHGC is the fraction of solar heat striking the window that eventually makes it to the indoors either by direct transmission or by absorption in the glass.

Visible transmittance, $\tau_{visible.}$ is the fraction of visible light that is transmitted through the window glass. Selective glass absorbs the infrared portion of the solar spectrum, thus reducing the SHGC, but lets the visible part of the spectrum pass, thus maintaining a high $\tau_{visible}$.

TABLE 6-3. PROPERTIES OF DIFFERENT TYPES OF WINDOWS

Type of window	U-value ($Watt/m^2C$)	U-value (Btu/ft^2Fhr)	SHGC	$\tau_{visible}$
Double-pane, clear glass	3.50	0.62	0.7	0.79
Double-pane, clear glass, SnO_2 low-e, non-metal frame	2.78	0.49	0.7	0.79
Double-pane, high-solar-gain, Ag/TiO_2 low-e, non-metal frame	1.70	0.30	0.60	0.60
Triple pane, low-e, argon fill, selective glass, wood frame	1.36	0.24	0.27	0.44

Source: LBNL 2011.

Window Overhangs

Sometimes solar heat coming in through a window is desirable and sometimes it is not. The difference in the position of the sun in winter from that in summer gives the overhang an ability to admit solar heat when it is wanted but exclude it when unwanted. A window overhang is described by two dimensions; the projection distance that the overhang edge sticks out from the plane of the window and the vertical offset height from the top of the window to the edge of the overhang. Figure 6-4 shows the geometry typical of the arrangement between a window and an overhang. Note that it is only the position of the edge of the overhang that matters—you may have flat or sloped, open or soffit, or gutter drip edge. There is no one overhang dimension that is perfect for all seasons. The sun is in the same position on both the spring and fall equinoxes, but in spring it is cold and we need heat, and in fall it is hot and we don't. Comfort is often achieved by movable awnings or a planted vine trellis that has no leaves in spring but provides shade in fall. However, it is possible to design a single overhang which provides complete shade at noon on the summer solstice and complete sun on the winter solstice, which seems like a good design criteria. For a window or row of windows of any length we can calculate the projection and offset of the overhang based on the altitude of the sun. On the summer solstice the declination is $\Delta = 23.45$ degrees and at noon the hour angle is $h = 0$ degrees. On the winter solstice, the declination is $\Delta = -23.45$ degrees; at noon the hour angle is $h = 0$ degrees, and the equation for the altitude angle of the sun reduces to

$$\alpha_{winter} = \sin^{-1}[\cos(\varphi)\cos(-23.45)\cos(0) + \sin(\varphi)\sin(-23.45)]$$

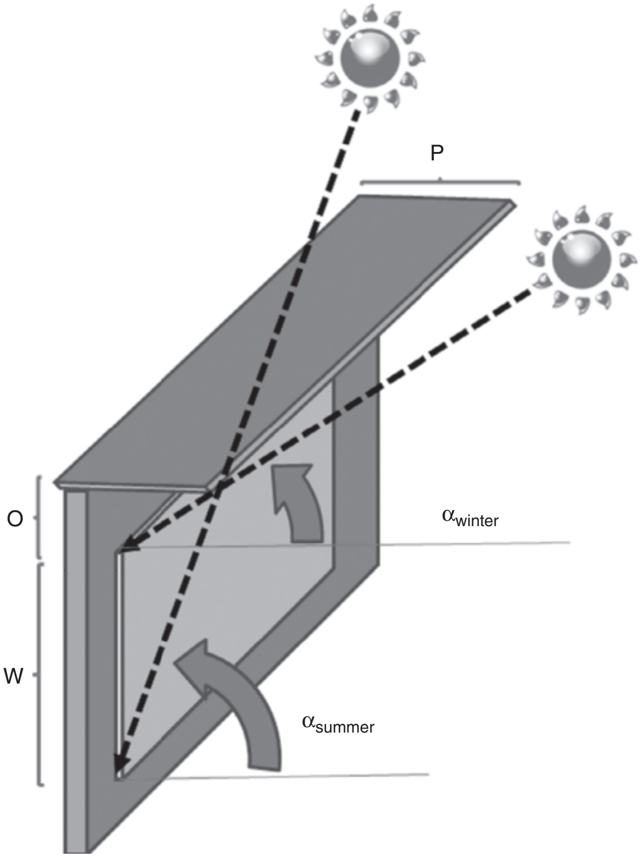


Figure 6-4. Horizontal projection and vertical offset of a window overhang as calculated from winter and summer solar altitude angles. (Figure by the author)

Where φ is the latitude of the building location. At noon on the summer solstice the altitude angle of the sun is

$$\alpha_{\text{summer}} = \sin^{-1}[\cos(\varphi)\cos(23.45)\cos(0) + \sin(\varphi)\sin(23.45)]$$

We have two equations (altitude angle winter and summer), so we can solve for the two unknowns (projection and offset of the overhang). The first, by substitution, the vertical offset distance between the top of the window and the overhang edge is

$$O = \frac{W\dfrac{\tan(\alpha_{\text{winter}})}{\tan(\alpha_{\text{summer}})}}{\left(1 - \dfrac{\tan(\alpha_{\text{winter}})}{\tan(\alpha_{\text{summer}})}\right)} \tag{6-16}$$

And then the horizontal projection of the overhang from the plane of the window is

$$P = (W + O)/\tan(\alpha_{\text{summer}}) \tag{6-17}$$

Example Calculation of Window Overhang Dimensions

Determine overhang dimensions that provide complete shade at noon on the summer solstice and no shade at noon on the winter solstice. The location is Cheyenne, Wyoming, latitude = 41.15N, and the height of the window, W is 2 m (6.6 ft). Table 6-4 lists the results of the solar angle calculated using equation 1-13, and then equations 6-16 and 6-17 to position the overhang.

Absorbing Surfaces

After sunlight enters the window of a room, it is incident on a room surface. It is desirable to position the thermal storage in direct sunlight, and for the surface of that mass to have a high solar absorptivity, α, the fraction of the optical, radiant incident energy retained and not reflected from the surface. Other, nonmass surfaces of the room should be light colors so that they reflect sunlight to the mass and so that they have less radiant heat loss. Table 6-5 top lists the solar absorbtivity of some common building materials.

TABLE 6-5. SOLAR ABSORBTIVITY OF COMMON ROOM SURFACES

Material	Solar absorbtivity
White paint	0.25
Concrete	0.65
Red brick	0.70

Source: PSIC, 1995.

THERMAL STORAGE

If the solar gain exceeds the daytime heat loss of a structure, thermal storage is needed to store the solar heat. Thermal storage extends the delivery of solar heat into the room hours after the sun has set in the evening. Although storage systems to store heat for a series of cloudy days or even seasonally from summer to winter have been demonstrated, they are in general prohibitively large and expensive. Research into storing heat by a reversible chemical reaction is promising, but still requires a large mass of reactants and chemical energy storage systems are expensive and not yet commercially available. Thus we focus here on sensible heat storage and advanced phase-change storage media.

Sensible Storage

"Sensible" storage media, such as concrete, brick, rock, or any mass, store heat associated with an increase in temperature. Over a period of time, the amount of energy stored in a mass of sensible media is

$$Q_{\text{stored}} = M_{\text{storage}} C_{p,\text{storage}}\,\Delta T_{\text{storage}} \tag{6-18}$$

TABLE 6-4. EXAMPLE CALCULATIONS OF OVERHAND DIMENSIONS FOR A WINDOW

W	Height of window	2.0 m	6.6 ft
φ	Latitude	41.2 degrees	
α_{winter}	altitude angle of sun at noon on the winter solstice Equation 2-13	25.4 degrees	
α_{summer}	altitude angle of sun at noon on the winter solstice Equation 2-13	72.3 degrees	
O	Vertical offset between overhang edge and top of window Equation 6-16	0.4 m	1.2 ft
P	Horizontal projection from plane of window to edge of overhang Equation 6-17	0.75 m	2.5 ft

Where M_{storage} is the mass of the storage medium (kg or lbm), $C_{\text{p},\text{storage}}$ is the specific heat (kJ/kg/K or Btu/lb/F), and $\Delta T_{\text{storage}}$ is the temperature at the end of the period of time minus the temperature at the beginning of the period. As heat is added, $dT_{\text{storage}}/\text{dt}$ is the rate at which the temperature is increasing and dT is positive, if the mass is cooling down, dT is negative. This change in temperature is unfortunate because we seek a constant temperature in the room. The amount of heat that we can store in the mass of a room is limited by the temperature fluctuations we are willing to tolerate in the room. What we are willing to tolerate is on the order of $\Delta T_{\text{storage}} \leq$ 4C (8F) (ASHRAE 2010), but it depends on the humidity and how many articles of clothing we are willing to put on…or willing to take off. For mass separate from the room, such as a rock bin or water tank, a $\Delta T_{\text{storage}}$ of 20 C (40F) is achievable, bracketed between a high temperature at which heat loss off the whole system (solar collectors, etc.) is excessive and a low temperature below which the heat is too low a temperature to be useful input to a heat exchanger with the room air.

Using such a criteria for $\Delta T_{\text{storage}}$, we can determine the amount of mass that would be required to store the incident daily solar resource.

$$M_{\text{storage}} = \frac{A_c K I_{c,\text{day}} SHGC}{C_{p,\text{storage}} \Delta T_{\text{storage}}} \qquad (6\text{-}19)$$

In this chapter we talk a lot about thermodynamics, which is where the energy (kWh, Btu) comes from and where it goes, but here *transport phenomenon*, which concerns the rate at which energy is transferred, becomes important. Transport phenomenon are heat transfer (convection and conduction) and fluid mechanics (air flow). There must be enough surface area of the mass in communication with the solar resource and in communication with the room to affect the transfer of energy in and out of the mass. It is my opinion that in passive systems, the mass must be directly illuminated by the sun in order to participate in the storage of solar thermal energy. Solar energy absorbed on the mass surface can go into the mass by conduction or can go into the room air by convection. In order to steer more heat into the mass, it is important that conduction into the mass be maximized.

The floor in front of a window is the most obvious surface on which to absorb the incident radiation. A finished concrete floor might be best for this, but tile fully bedded in mortar probably has good contact, too—wood floors or carpeting would tend to prevent solar heat from entering the mass floor and would thus contribute to overheating of the room, by steering solar heat into the room air rather than the mass. Massive walls, or frame walls with a double-thickness of drywall, are also used to add mass to a space, but consider the geometry of how the sunlight comes in the window and remember that only mass positioned in the direct sunlight may be expected to store solar heat. Positioning the mass between the source of solar heat and the room smooths out the temperature fluctuations in the room and is the intent of the thermal storage wall concept. (Thermal storage walls are also called "Trombe walls" after their French inventor). M_{storage}, mass in a room, is insulated on the outside and exposed to both solar radiation and room air on the inside. At the surface of the mass the energy balance between incident solar, conduction into the mass, and heat delivery to the room air may be written:

$$A_{mass} K I_c \alpha SHGC - A_{mass} h (T_{\text{surface}} - T_{\text{air}}) - \frac{A_{mass} k_{\text{mass}} dT_{\text{surface}}}{dx} = 0 \qquad (6\text{-}20)$$

The surface itself has no thickness and thus no mass. The surface area of the mass is A_{mass} (m^2). Here A_{mass} is taken as the same area (m^2, ft^2) as the window, which would be the case only if the mass were directly in front of the window like a thermal storage wall. But with this simple geometry we can make two important points:

1. In order to drive the heat into the mass, we need a high surface temperature; this is of no consequence on the outside of a thermal storage wall where there is no occupancy, but difficult to achieve on room surfaces. Temperatures on the black outside surface of a thermal storage wall may exceed 60 C (140F).
2. In order to minimize T_{surface}, we need a storage mass with a high thermal conductivity. This property is listed as of being of equal importance to density and specific heat in table 6-6. Dense concrete is good but some types of brick and plasters have low thermal conductivity.

T_{air} is the temperature of the air near the mass surface, for direct gain spaces this would be the room air T_{room}, but for a thermal storage wall the air between the glazing and the mass gets much hotter than a room. The solar absorptivity of the mass surface is α, h is the convective heat loss off the mass surface, which is around 4.2 W/m^{2}C for a vertical wall and about 5.5 for a horizontal floor surface. The thermal conductivity of the mass is k_{mass} and x is the depth into the mass.

A very simple estimate of the required thickness of mass, X (m or ft) is based on the amount of heat that we want to store

$$X = \frac{(A_c I_{c,\text{day}} \alpha SHGC)}{\Delta T_{\text{storage}} \rho C_p A_{mass}} \qquad (6\text{-}21)$$

Where A_{mass} is the exposed area of the slab of mass. The Biot number is the ratio of convective heat transfer to the room divided by conduction into the mass (Incropera and DeWitt 2005). We seek a Biot number where the convection is an order of magnitude lower than conduction

$$Bi = \frac{hX}{k} < 0.1 \qquad (6\text{-}22)$$

For an h value of 5 W/m^2/C and a mass thickness of 0.1 m, we would need a thermal storage mass material with a conductivity of 5 W/m/C or more. This is difficult to find in common building materials but not impossible. Table 6-6 lists out the thermal properties of several building materials that might be

TABLE 6-6. THERMAL PROPERTIES OF SENSIBLE STORAGE MATERIALS FOR PASSIVE SOLAR CONSTRUCTION

Material	Density (kg/m^3)	Specific heat (J/kgC)	Thermal conductivity (W/m/C)
Concrete (dense)	2100	840	1.40
Concrete (light)	1200	1000	0.38
Brick (clay)	1700	800	0.62
Brick (carboundrum)	3010	835	18.0
Stone (limestone)	2180	910	1.5
Stone (granite)	2630	775	2.79
Stone (quartzite)	2640	1105	5.38
Gypsum drywall	950	840	0.16

Source: Incropera and DeWitt 2005

considered for thermal storage. Sioux quartzite has a conductivity of 5.38 W/m^2/C. Rock or brick with a crystalline structure has higher conductivity than other types of stone, and metal such as reinforcement rod within concrete conducts heat deep into the mass.

WATER THERMAL STORAGE TANKS

Water is an excellent storage medium because it has a high specific heat and convective currents easily absorb heat into the mass of water and release it again, helping to maintain a uniform temperature. One of my first jobs as a college intern at the Solar Energy Research Institute was to disassemble sunspace tests which involved 55-gallon drums of storage water. I've also seen thermal storage water in a wall built of used wine bottles. I visited the passive solar building built for the Society for the Preservation of New Hampshire Forests, and storage was provided by tall cylinders filled with water. The cylinders are fiber-reinforced plastic tubes manufactured by Kalwall. Each 12-inch-diameter tube is 8 feet high and contains 47 gallons of water weighing 404 lbs. Recalling our definition of a Btu as the energy to heat 1 pound of water by 1F, the tube would store 3,200 Btu of heat (about 1 kWh) as it went through our allowable temperature fluctuation of 8F (4C). Employees had floated plastic fish in one of them. The supplier claims that they store the same amount of heat in 60 percent less space and 80 percent less weight than concrete (Solar Components Corporation 2010). The cost of each fiberglass tube is listed as $159/each, and additional costs may include floor reinforcement and a tray with a drain to mount them in should they ever leak. For discussion of water thermal storage tanks in active heating system, see chapter 4, "Solar Water Heating."

ROCK BINS

Sensible storage may be achieved by flowing air through a bin of rocks. The rocks should be rounded, so that they leave voids for the air to flow around them. Diameters of two to four cm (one to two inches) are probably ideal. A fan is required but the forced convection and the large surface area solve the problem of how to get the heat into the mass. A rock bin is likely to be found in an active system that gets the heat from air-heating flat plate collectors. George Löf of the Solar Energy Applications Laboratory was a proponent of air heating systems with rock bin storage, and claimed that they could achieve the same efficiency as liquid systems without risk of fluid freezing or leaks. But I have found them problematic for the following reasons: in order to optimize the heat transfer the direction of airflow should be reversed when putting heat in or taking it out of the rock bin requiring two fans or actuated dampers; dust and dead insects, potential allergens, accumulate in the rock bin; the ducts are large and more expensive than pipe; and the fan power exceeds the pump power that would be required in liquid systems.

Phase Change Storage

If we are attempting to offset a large percentage of the heating load with solar, it is not possible to engage enough mass using only sensible heat to store the amount of solar heat required and still keep the temperature in the space relatively constant. I did some modeling with the SERI-RES computer program and came to the conclusion that phase-change materials would be needed in a passive-solar approach to net-zero energy use. Phase-change materials (PCMs) have been fabricated into plastic-enclosed panels that fit between the studs of frame construction and have been made into pellets incorporated into drywall. It is also easy to fill plastic tubes with PCM. PCMs store heat through a change of phase rather than a sensible temperature increase. So if the transition temperature of the material is within the comfort range of the space, they keep the temperature very constant. The change of phase also stores a large amount of heat so less mass is required.

$$Q_{\mathrm{stored}} = M_{\mathrm{storage}}[C_{p,\mathrm{storage}}\Delta T_{\mathrm{storage}} + \lambda_{\mathrm{storage}}] \qquad (6\text{-}23)$$

Where $\lambda_{\mathrm{storage}}$ is the "latent heat" of the phase change material—the amount of heat in J/kg or Btu/lb that is absorbed or released as the material changes from one phase to another at its transition temperature or over a range of transition temperatures.

I think that due to temperature range, flammability requirements, cost, longevity, and other issues the only PCM available for solar passive solar heating are salt hydrates. Salt hydrates store heat by liberating water from a crystalline salt structure and then release heat as water is re-absorbed. The temperature at which this phase change occurs, the "transition temperature" may be adjusted by the selection of the salt chemistry and the concentration of water. Suitable salt-water mixtures have the same composition in the liquid phase as they do in the solid phase (so called "eutectic" salts)- otherwise the change of phase would be spread out over a large temperature difference and solid salt particles would separate from the mixture. Glauber's salt ($Na_2SO4 + 10\ H_2O$) is an example. Figure 6-5 shows a phase-change panel product called Energyphase previously manufactured by Dow. As listed in Table 6-7, Glauber's salt stays at its transition temperature of 32 C (94 F) as it stores about 250 kJ/kg (106 Btu/lb) upon a change of phase. By comparison, the same mass of concrete would have to cool from 60C (140 F) to 0 C (32 F) to release the same amount of heat. Salt hydrates must be encased in a sealed container to keep the water from evaporating. Companies such as PCM Products Inc. supply stabilized phase change compounds in almost any range of transition temperatures (PCM Products Inc. 2011). A reference with thermal properties of just about every phase-change material imaginable is in Demirbas 2006.

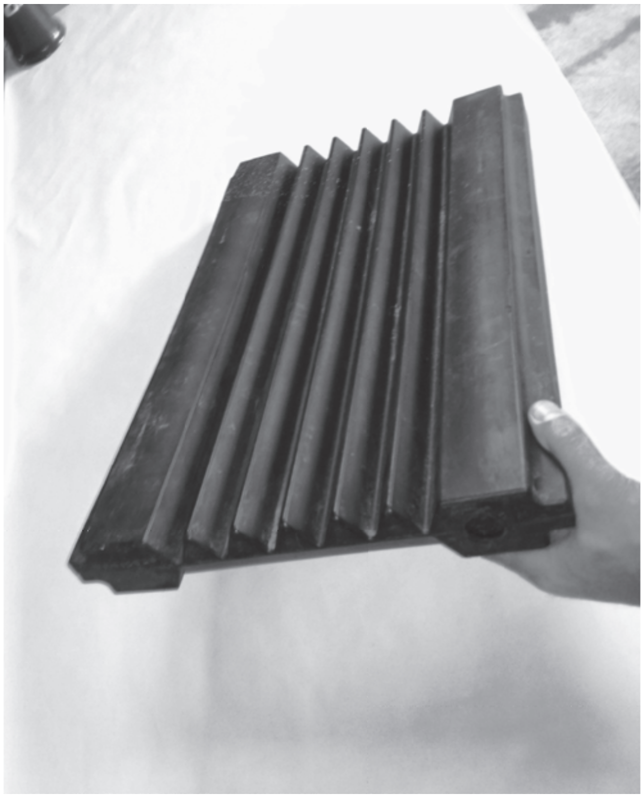


Figure 6-5. This phase-change panel is encapsulated in a plastic shape that fits between studs in a frame wall. The 10-kg (22-lb) panel stores 2500 kJ (2,332 Btu) as latent heat. (Photo by author)

TABLE 6-7. THERMAL PROPERTIES OF PHASE CHANGE STORAGE MATERIALS FOR PASSIVE SOLAR CONSTRUCTION

Material	Density (kg/m^3)	Latent heat (kJ/kg)	Transition temperature (C)
Glauber salt	2100	254	32 (94F)

HEAT DISTRIBUTION SYSTEMS

In passive solar heating systems, heat is distributed within a room by natural convection and radiation in the room, but active solar heating circulates a fluid to distribute heat to rooms. Here we consider three types of heat distribution systems, which are used to distribute heat into the rooms to be heated: radiant floor slabs, baseboards, and fan-coil units. Heat transfer from heating fluid at temperature T_{fluid} to room air at temperature T_{room} is given by the expression

$$Q_{heating} = h_{dist}A_{dist}(T_{fluid} - T_{room}) \tag{6–24}$$

Where h_{dist} is the heat transfer coefficient of the heat distribution element in a room, and A_{dist} is the surface area of the heat distribution element.

We see from this equation that there are three ways to get the amount of heat out of the distribution system that we need to meet the heating requirement of the room:

1. increase A_{dist}, the surface area of the heat distribution element. In the case of radiant floor heating this means putting the tubing circulating the heating water through the floor slab closer together; for baseboard heating it means extending the length of the baseboard heaters in the room, and for a fan coil it means increasing the surface area of the coil.
2. increase h_{dist}, the heat transfer coefficient. This is only practical by increasing the fan power of the fan-coil unit, as the radiant slab and baseboard both rely on natural convection.
3. increase T_{fluid}, the temperature of the heating fluid. This is the least desirable way to increase heat transfer because the efficiency of solar collectors, heat pumps, and even condensing fuel-fired boilers is reduced as the operating temperature is increased.

Radiant Slab

The efficiency of both solar water heating collectors and heat pumps goes down as the delivery temperature goes up. So it is desirable to have a heat distribution system with a low input water temperature. Because of the large surface area created, a concrete slab with tubes embedded in it for radiant heating has the lowest allowable inlet temperature of the heat distribution methods and is commonly used in systems that use solar collectors and/or heat pumps as the source of heat. The floor slab itself also provides the thermal storage. Figure 6-6 shows a manifold distributing heating fluid to an array of tubes in a radiant slab.

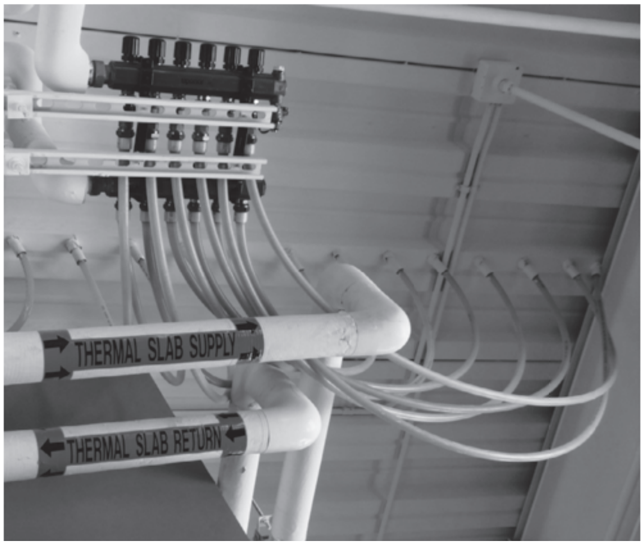


Figure 6-6. Extensive networks of tubes installed within concrete slabs form a radiant slab heat-exchanger. (Photo by the author)

Figure 6-7. A fan-coil unit consists of a finned coil, motor and fan, and this one includes condensation drip-pan and two electric heating elements. (Photo by the author)

The plastic tubes used in such a radiant floor have a sophisticated construction to perform the different functions required to contain the fluid, exclude oxygen from penetrating into the system, and resist damage to the tube over a very long lifetime. The other components of a radiant slab heating system are typical of any hydronic heating system.

Baseboard Heat

Baseboards are inexpensive and deliver heat to the perimeter of a building where heat loss occurs. However, due to limited surface area their design usually entails a high delivery temperature. Baseboards are typically sized for 70 C (160 F) inlet temperature, but for use in solar systems they must have a very large surface area (place them everywhere on the perimeter) in order to have adequate heat transfer from the 50 C (120 F) fluid typical of solar collector delivery. Baseboards show a lot of damage in high-use areas and they interfere with the placement of furniture flush against a wall.

Fan-coil Units

Fan-coil units, such as that shown in figure 6-7, may stand alone or be integrated into the ductwork providing and recirculating ventilation air to a room. Fan-coil units may be designed with a large enough surface area to work with a low input temperature. The size of the coil must be significantly larger with the 50 C (120 F) inlet temperature typical of solar systems than the size typical of systems that are heated to 60 C (160 F) by a fueled heater.

SOLAR SPACE HEATING (PASSIVE OR ACTIVE) SYSTEM SCHEMATIC DESIGN

Schematic design specifies the size, type and relative position of major elements of the design.

Passive Approaches to Space Heating

The word “passive” means that the system does not require electricity to run fans, pumps, or controls. Passive solar strategies include sun-tempered, direct-gain, sunspace, and thermal storage (Trombe) wall.

SUN-TEMPERED

“Sun-tempered” is just conventional construction, but with the windows with the right size and orientated to admit solar heat in winter and offset heating load. Since there is no additional thermal storage, the amount of solar heat incident in the day (Equation 6-11) should not exceed the heating load that occurs over the day. Thus

$$E_{\text{solar,day}} < [(UA)\Delta T - P_{\text{internal}}]*(\text{sunhours}) \tag{6-25}$$

Where *sunhours* equals the hours per day over which the solar heat is distributed.

Here we adopt a convention that 1 kW/m^2 represents “full sun,” and

$$\text{sunhours} = \frac{E_{\text{solar,day}}}{\left[1\frac{kW}{m^2}\right]} \tag{6-26}$$

For example, if our calculation of $E_{\text{solar,day}}$ indicates to us that 3 kWh/m^2/day came through the window, that would here be interpreted as 1 kW/m^2 for 3 hours. Without any storage, the maximum fraction of the heating load that can be met over a day is

$$SF = \frac{E_{\text{solar,day}}}{E_{\text{heater,day}}} \leq \frac{\text{sunhours}}{24} \tag{6-27}$$

Where the 24 in the denominator refers to the total number of hours per day.

DIRECT GAIN

The term *direct gain* means that sunlight is admitted directly into the living space. Direct gain increases the solar contribution over that of sun-tempered by making the windows bigger and by including thermal storage in the form of mass or phase-change materials. Direct-gain designs are often implemented with standard construction of windows and massive floor slabs as illustrated in the schematic diagram of Figure 6-8. Thus construction costs are usually less than sunspaces or thermal storage walls. Carefully implemented direct solar gain may contribute to daylighting objectives and allows views to the outdoors. Direct sunlight in the space causes some problems too: if the sunlight is incident on a computer screen nobody will be able to read the screen due to glare; if the direct sun is incident on a person sitting at a workstation that person will not be comfortable. This is because ASHRAE comfort criteria involve not only air temperature but "mean radiant temperature," and the sunlight is too intense for comfort. Large amounts of glass in the space may cause excessive heat loss in cold climates, but we mitigate that with premium windows. The purpose of large windows may be defeated with blinds if occupants have problems with glare, discomfort, or privacy.

Published rules of thumb for "typically insulated" direct-gain spaces say that the ratio of window area, A_c, to floor area of the room should be 0.1 to 0.2 in moderate climates (35 to 45 F) and 0.2 to 0.3 in cold climates (20 to 30 F) (Steven Winter Assoc. 1997). Another rule of thumb from the same handbook says that the ratio of the window area to the mass surface area should be around 0.3, and that the mass floor should be 10 cm (4 inches) thick. These two rules of thumb seem to combine to indicate that a window 2 m (6 ft) tall could heat a room only 6 m (18 ft) wide. But these rules of thumb were developed using a heat loss coefficient of 45 W/C/m^2 (8 Btu/degree day/ft^2) which corresponds to 200 ft^2 (20m^2) floor area room with R-2 windows (hrft^{2}F/Btu, double pane, low-e); R-25 walls and R-40 roof. Clearly, in order to heat a larger room, or to fit our passive solar features on the available south wall area, we need to reduce the loss coefficient below that of "typical," so that our passive solar systems are of a size which fits on the south wall of the room. Continuing this example, the insulation is improved by using triple-pane windows with an insulating value of R-4, and increasing the wall insulation to R-40. Increasing the roof R-value does not change the result much due to diminishing returns since it is already well insulated. These changes reduce the loss coefficient by half, the required solar system would only be half the size, and a 1 m (3 ft) tall window could provide enough heat to offset the heat loss from the 5.5 m (18-foot)-wide room. This example stresses the importance of triple-pane windows with very low loss coefficients and thick, continuous insulation in passive solar design.

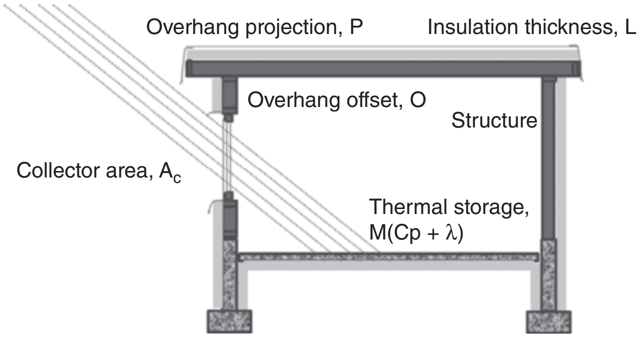


Figure 6-8. Schematic diagram of direct-gain passive solar space heating system shows the arrangement of major components: window, overhang, mass, and insulation. (Figure by the author)

The large window size can offset room heat loss and still have additional heat to impart to thermal storage. Here the objective might be to meet any part of the daily heating load, but in general it is not possible to store more than one day's heating requirements and we consider the load over the course of a 24 hour day:

$$E_{\text{solar,day}} < [(UA)\Delta T - P_{\text{internal}}]*(24 \text{ hours}) \tag{6-28}$$

On especially cold or cloudy days, the solar would meet a small fraction of the heating requirement and the balance would have to be made up by an electric or fuel heater. But on an average day we can strive to meet up to any fraction of the load with solar

$$SF = \frac{E_{\text{solar,day}}}{E_{\text{heat,day}}} \leq 1 \tag{6-29}$$

SUNSPACE

The energy contribution of a sunspace should be measured relative to the space adjacent to the sunspace that is being heated by the sunspace. The sunspace itself does not usually count as rentable space because, while it may be pleasant at most times, it is not kept at a uniform temperature. The large window area makes overheating likely in the daytime and the space gets too cold for comfort at night. But by allowing the temperature in a sunspace to vary, it can make a positive energy contribution to the heating of the space behind it. During the day, the wall between the sunspace and the room is heated by the sun. After the sun goes down, air from the overheated sunspace can be circulated into the room to offset heat loss and save fossil fuel. If we tried to heat the sunspace to comfort conditions at night, it would be a net energy loser because it has too much glass.

Figure 6-9 shows the components of a sunspace system and an adjacent room. It is possible to vent the hot air from the sunspace into the adjacent room during the day except for two considerations: the room probably won't need the heat during the day, rather at night, and venting the sunspace will reduce its temperature lower than the high surface temperature required to force conduction of heat into the thermal storage mass for use at night. Significant mass in the wall between the sunspace and the room to be heated provides thermal storage and a transfer of heat from the sunspace in the daytime to the room at night. I have glass doors between the two sunspaces and the living area in my home. I keep them closed as the sunspace overheats during the day and at night I open the doors and I can feel the heat come into the living area.

As with direct-gain spaces, the rule of thumb for mass area in a sunspace is that the area (m^2, ft^2) of the mass surface area is three times the window area, A_c, and that the mass floor be at least 0.1 m (4 inches) thick. The thickness of the mass wall between the sunspace and the room to be heated is at least 0.2 m (8 inches) inches. The wall should be a solid dense mass such as concrete without voids or breaks in the thermal conductivity. A section later in this chapter shows how to size collector area and mass for a given load, but for now let's consider the published rules of thumb for "typical" insulation levels. These show that the sunspace window area as a fraction of the room floor area should be from 0.33 in temperate climates (45 F) and midlatitudes (36 N) to 0.99 in moderate climates (35 F) and high latitudes (48 N). And from 0.65 in cold climates (30 F) and midlatitudes (36 N) to 1.50 in cold climates (20 F) and high latitudes (48 N) (Steven Winter Assoc. 1997). Although the sunspace may project from the house, achieving a glass area larger than the floor area and still have it strike the mass wall directly is probably geometrically impossible. It is clear that we must improve the insulation of the envelope rather than make the sunspace bigger. Replacing the "typical" insulation with triple-pane windows and R-40 wall systems (ceiling is already well insulated at R-40 in this example), would allow us to heat a room in a cold climate at high latitude with glass that is of an area 75 percent that of the floor area to be heated- still challenging to fit into the architecture but technically not impossible.

THERMAL STORAGE (TROMBE) WALL

A thermal storage wall is like a sunspace without the space. The massive concrete or masonry wall is built directly behind the glass of the window as shown in the schematic diagram of figure 6-10. Although both vented and unvented thermal storage walls have been built, I feel that the ones that do not have vents into the room are better because they force a high temperature on the outer surface of the mass, and that is required to drive the heat into the mass by conduction. A "selective surface," similar to that of a solar thermal collector, is recommended in order to achieve a high absorptivity of solar radiation but a low emissivity of infrared heat loss. However, care must be taken to make sure that the selective surface, which is usually deposited on a metal foil, is in good thermal contact with the concrete thermal storage wall (which is difficult to achieve); otherwise black paint would be better.

A thermal storage wall does not allow the solar radiation to enter the living space, avoiding problems with glare. It also affords privacy but blocks the view. There is a thermal storage wall on the south side of the restroom at the Great Sand Dunes National Monument in Colorado. The footer and foundation have to be constructed to support the weight of the thermal storage wall, and special building codes such as seismic codes would have to be observed. Separate windows would have to be provided for views and daylight. All the solar heat has to go through the mass so there is no peak in the daytime temperature as might occur with direct-gain.

The area (m^2, ft^2) of the mass involved is the same as the window area, A_c. The section below shows how to size collector area and mass for a given load, but published rules of thumb for "typical" insulation levels show that the window area as a fraction of the room floor area should be from 0.25 in temperate climates (45 F) and midlatitudes (36 N) to 0.55 in moderate climates (35 F) and high latitudes (48 N). And from 0.50 in cold climates (30 F) and midlatitudes (36 N) to 0.98 in cold climates (20 F) and high latitudes (48 N) (Steven Winter Assoc. 1997). Here again, it is clear that if we want to meet a high fraction of the heating load by a thermal storage wall system that can fit on the south wall of our building, we must improve the insulation of the envelope. Replacing the "typical" insulation with triple-pane windows and

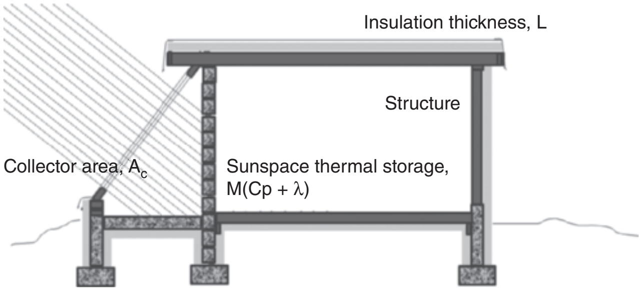


Figure 6-9. Schematic diagram of sunspace passive solar heating system. While a sunspace may be furnished and comfortable at most times, its temperature will vary. (Figure by the author)

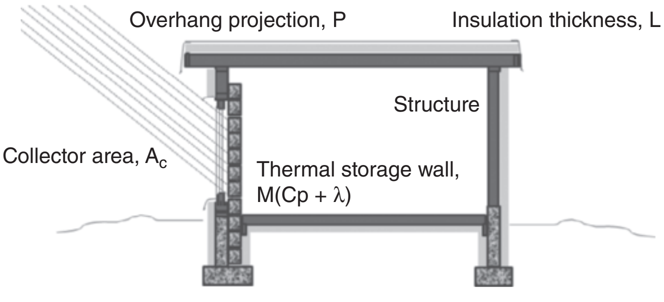


Figure 6-10. Schematic diagram of thermal storage wall (Trombe Wall) passive solar heating system. A high surface temperature conducts heat into the mass. (Figure by the author)

R-40 wall systems (the ceiling is already well insulated at R-40 in this example), would allow us to use only 50 percent of the south wall area for our thermal storage wall area, A_c to heat our room.

Photovoltaics/Heat Pump System for Space Heating and Cooling

Chapter 3, on photovoltaics, describes how PV can deliver electricity to a building electrical panel. Many utilities have "net-metering" arrangements that allow PV generation in excess of the building load to be saved as a credit, for use without cost up to 12 months later. If such a policy is available to your solar building project, you can think of the utility as a 100 percent efficient, free battery for storing electricity from summer, when sunlight is plentiful, to winter, when it may be used to heat the building with a heat pump. Figure 6-11 is a schematic diagram that combines photovoltaics and heat pump technologies to deliver space heating and cooling.

A "heat pump" is a device, similar to an air conditioner, with a motor and compressor; a condenser, an evaporator, and an expansion valve. Electric power is used to run the motor which turns a compressor, compressing a refrigerant vapor to a higher pressure and temperature. The superheated vapor then condenses, imparting its latent heat to the fluid circulated for heating; the compressed liquid is then expanded to a lower pressure across an expansion valve, and the liquid absorbs heat in the evaporator, absorbing heat from water circulated in a ground loop as in the case of a ground-source heat pump or from ambient air as in the case of an air-source heat pump. Most heat pumps include a "reversing valve" which switches the position of the condenser and evaporator, allowing the same machine to be used for both heating or cooling of a space.

Not everybody can net-meter, because if too many people on a utility circuit have PV, there would be no place for the excess PV energy to go. But if your utility allows net-metering, then using PV power generated in summer to run a heat pump in winter is one of the few practical ways to do solar space heating.

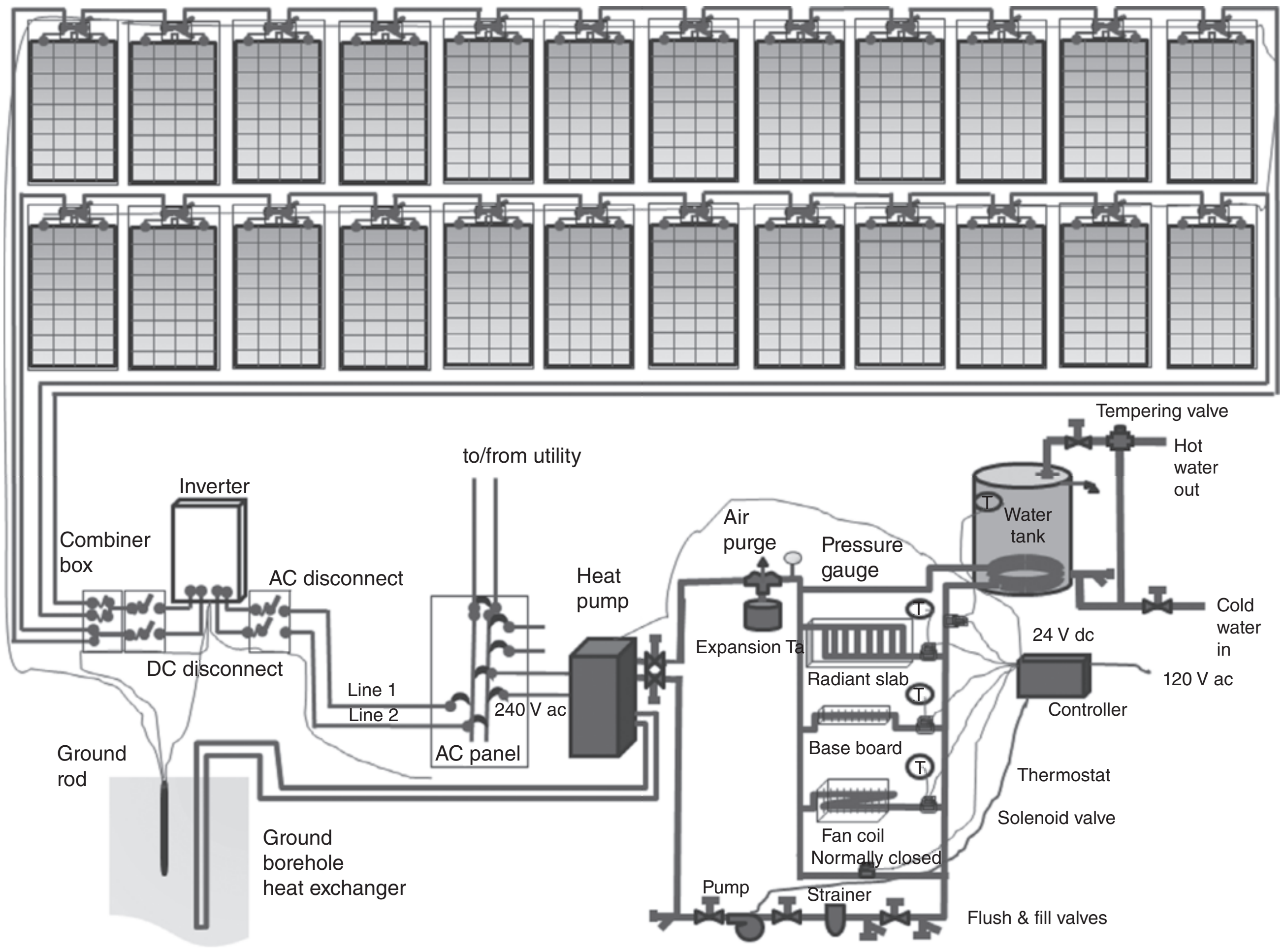


Figure 6-11. Schematic diagram of PV combined with ground-source heat pump to provide heating and cooling for a building in combination with utility power and a net-metering policy. (Figure by the author)

The heat pump may draw from or reject heat to the ground using a ground heat exchanger. The ground heat exchanger is built by drilling a borehole 250 to 400 feet deep and inserting a plastic pipe in and out of the borehole. There are also other configurations to bury coils of plastic pipe in the ground or in building foundation elements to create a heat exchanger with the soil. The size of the heat pump and the number of boreholes required depends on the heating and cooling capacity required, and the effectiveness of heat transfer with soil and groundwater.

Active Solar Thermal Space Heating System

We have already described how solar heat can be used to heat a heat-transfer fluid in chapter 4. There the discussion was just how to heat a tank of water, but such a system could be used for any heating purpose including space heating. Systems have been built that store heated water in large tanks or cisterns and then use that solar heated water to heat the house. However, in my experience the water tank needs to be too large to store a significant part of the space heating load and is thus rather impractical. A preferred approach is to use the mass of a radiant floor slab to store the solar heat available during the day, and then that slab can release its heat into the room over 24 hours.

Figure 6-12 shows a schematic diagram of an active solar space heating system. A “primary loop” is powered by one pump and “secondary loops” associated with the boiler, solar panels, storage tank, and load may be powered by separate pumps. For example, if the solar system is delivering heat in the middle of the day when nobody is home, the solar loop, primary loop and storage loop would be circulating. Then at night the storage loop, primary loop, and floor slab loop would be circulating. It is not recommended to circulate fluid through components, such as the boiler, that are not in use at the time due to heat loss. If the primary loop pump is powerful enough, flow can be forced through the other loops with venturi tees, and the unused components valved off with normally-closed solenoid actuated valves.

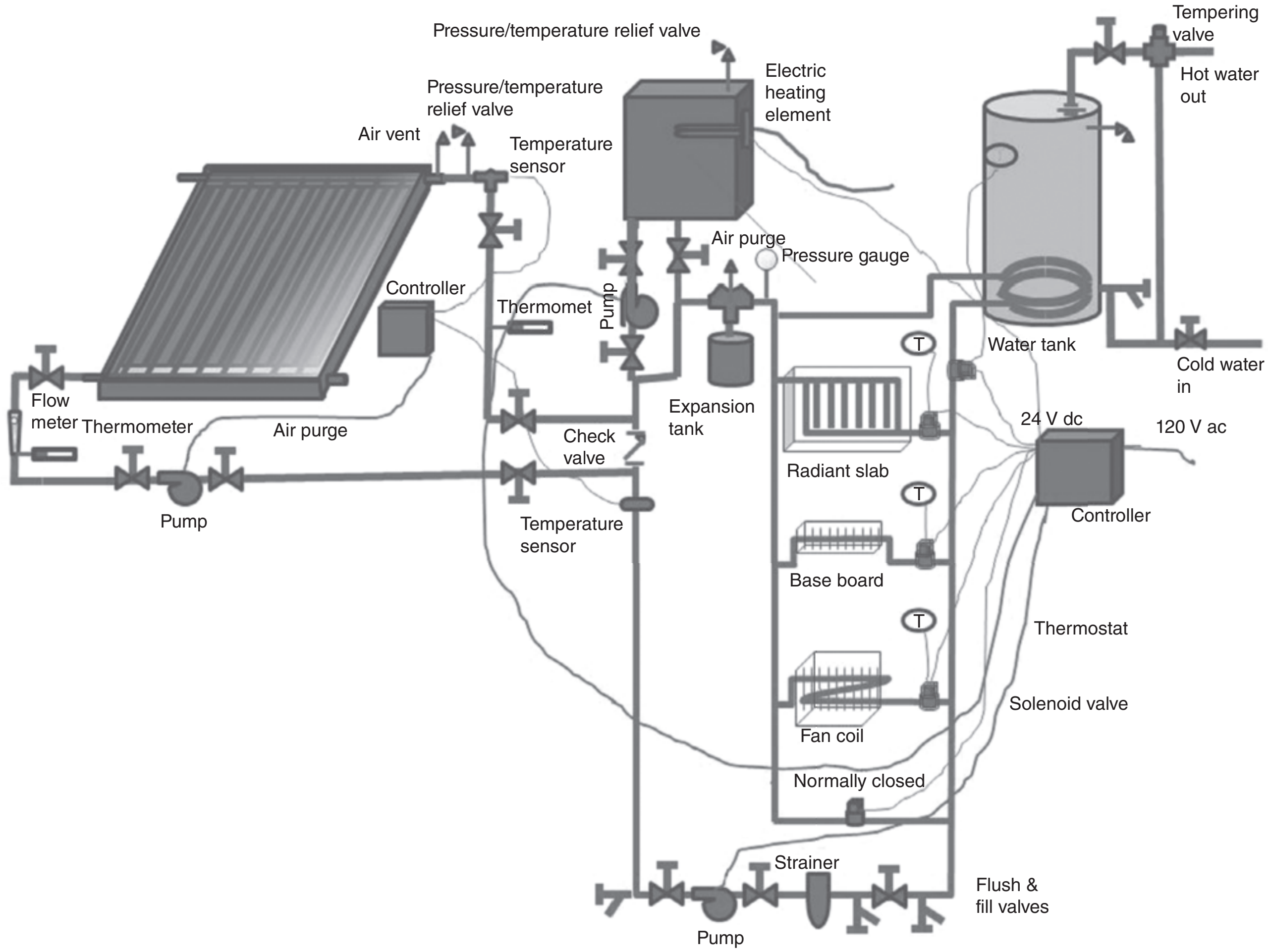


Figure 6-12. Schematic diagram of active solar thermal space heating system, with components similar those of any hydronic heating system. (Figure by the author)

The controls of a solar space heating system are more complicated than a conventional heating system. In a conventional heating system, a heater turns on when the space temperature drops to a low set point, and then turns off when it reaches a high set point. In a solar heating arrangement, the pump on a solar loop will start running whenever the temperature of the solar collector exceeds the temperature in the primary heating loop by a set degree. We seek for the temperature rise as it goes through the solar collector to be on the order of 10 C (20 F), which is about twice that used for potable-water heating only. This is because a higher temperature is required for the space heating heat exchangers and to force heat into the thermal storage of a mass floor. The flow rate through the collector should be around 0.8 liters per minute per square meter of collector (0.02 gallons per minute per square foot of collector) when water is the heat-transfer fluid. Other flow rates apply for different heat transfer fluids (Energy Savers 2009). The pump on the primary heating distribution loop will run when the solar pump is on or when the control valves on any of the heating zones are open. Since we are trying to store solar heat in the mass of the room, the control valves to the hot water tank or the radiant floor slab are open unless the temperature of those components reaches a set high-limit. Similarly, the control valves to baseboards or fan coils are open unless the room temperature reaches a set high limit. The set high-limit may be on the order of 80 C (180 F) for the water tank, 35 C (94 F) for the floor slab and 27 C (80 F) for the room temperature. Thus the components of the heat distribution system are open to accept solar heat whenever it is available, and close only to avoid overheating.

If the temperature in the room drops lower than a low set point, around 18 C (65 F), then an auxiliary electric or fuel-fired heater will either heat the primary loop or heat the room directly.

Thus, whereas a conventional heating system uses a simple thermostat contact-closure to close relays and power the pump and heater, the solar controls are complicated to the point that a programmable logic controller is often used to control power to pumps and fans and to control the position of solenoid valves. Notice that each thermostat performs two operations rather than just one operation: stop the solar heat input when the room is overheated, and start the auxiliary fossil-fueled backup heater when the room reaches a low set point.

Solar Absorption Space Cooling by Active Solar Thermal System

In 1876, Augustin Mouchot, used a boiler in the focal line of a large truncated cone to generate steam. At the Universal Exposition in Paris in 1878, Mouchot combined this with an ammonia-cycle absorption cooler invented by Ferdinand Carre. The solar powered machine delivered cooling and stored it in the form of ice that could be brought out when needed (Butti and Perlin 1980). I think it's interesting that neither inventor could have demonstrated solar cooling alone—they had to work as a team. Heat from an active solar thermal system may be used as the heat source for an absorption cooling machine. The pairs of fluids used in absorption cooling include: ammonia in water; water in lithium bromide; water in zeolite; methanol in activated carbon; and water in silica gel (Walker et al. 2003). A cooling effect is created as the ammonia evaporates from the water or the water evaporates from the lithium bromide in the "evaporator". The vapor is returned to liquid form by heat removal in a "condenser." A heat exchanger in the evaporator circulates the chilled water that is the product of the process. The vapor is absorbed into a more concentrated solution in the "absorber," releasing its latent heat. Heat is rejected to fluid that flows through a heat exchanger in the absorber and a second heat exchanger in the condenser, and then on to an outdoor cooling tower from which the heat is ultimately rejected to the ambient wet-bulb temperature if a wet cooling tower is used, or to the dry-bulb temperature if a dry fan-coil is used as the condenser. Solar heat is accepted into a heat exchanger in the "generator" of the absorption cooling machine, where the vapor is separated from the absorbing fluid. This requires a high temperature collector such as evacuated tubes or parabolic troughs.

A "double effect" uses the heat rejected from one absorption cooler cycle as the heat source for a second cycle. The performance of the absorption cooling machine is expressed as capacity (tons) and coefficient of performance (COP). A "ton" of capacity is enough cooling to provide one ton of chilled water per hour, or 12,000 Btu/hr (2,869 Watts of heat removal). The COP is the ratio of heat removed from the chilled water in the evaporator, $Q_{\text{evaporator}}$, to heat input, $Q_{\text{generator}}$.

$$COP = \frac{Q_{\text{evaporator}}}{Q_{\text{generator}}} \tag{6-30}$$

In order to maintain a COP greater than 1.0, the generator where the ammonia vapor is separated from the water should be at least 126 C (260 F), and this would require the solar collector to operate at approximately 136 C (280 F).

A conventional compression cooling system uses about 1.5 kW/ton of cooling. The components of an absorption cooler can be arranged so that the working fluids are moved by gravity, but pumps are required to circulate the chilled water through the evaporator and the heat rejection water through the absorber and condenser. These pumps require around 0.2 kW/ton, for a net savings in electricity of 1.3 kW per ton.

Solar Panels Plus out of Chesapeake, Virginia, combines their evacuated tube solar collectors with absorption cooling machines manufactured for this purpose by Yazaki in Japan. McQuay-Sanyo also makes an absorption cooler. Bergquam Energy Systems has installed several systems in California in sizes from 4 to 20 tons and they have operated for over

20 years. The cost of an absorption cooling machine is on the order of $1,700 per ton. A large storage tank, about 50 gallons per ton, is required to stabilize operation of the heat transfer processes, and adds a cost of around $500 per ton. Cost of a complete installed system is around $7,500 per ton, an optimized system could get this down to $5,000 per ton (Bergquam and Brezner 2003).

Solar Dessicant Dehumidification and Cooling

In humid climates a large part of the air conditioning load is removing moisture from air instead of reducing its temperature. Desiccants may be used to absorb the water vapor from the air, and then may be regenerated with solar heat. This regeneration may be accomplished by rotating a solid desiccant wheel between the stream of air to be dehumidified and a second stream of air to which the moisture will be rejected. It can also be accomplished by circulating a solution of water and desiccant such as lithium bromide. Absorption releases the latent heat of the water so the air dried and thus heated is passed through a heat exchanger to cool it back down, and then, if a lower temperature is desired, the product air is passed through an evaporative cooler to reduce the temperature of the air. The other side of the heat exchanger preheats air coming back from the space, which is warm but usually at a lower humidity than the outside air, and that air is heated further by solar heat from an evacuated tube or other well insulated solar array, and if that is not at a high enough temperature to regenerate the desiccant, the air is heated further by a fuel-fired furnace, and then passed through the desiccant media to remove the moisture from the media. The lower temperatures required for regeneration offer another hopeful technology for feasible solar cooling (Walker et al. 2003).

ESTIMATING THE COST OF A SOLAR SPACE HEATING SYSTEM

Initial Cost Estimate

Since passive solar strategies are implemented with building materials and systems (walls, windows, floors), the cost of a system is estimated using architectural construction estimating techniques and information sources. The schematic design establishes the information required to prepare a cost estimate. The cost estimate itemizes each component, and the installation labor associated with each component or the building project as a whole. Adders account for overhead, profit, or any other cost adders that can be considered "percent of project." Cost estimating manuals published by RSMeans are an excellent reference for the cost of building systems such as windows and concrete walls and they also have an "Assemblies" section of each book which includes, for example: solar direct-gain glazing; passive solar indirect-gain wall; passive solar sunspace; geothermal heat pumps systems; and other systems such as PV and solar hot water (RSMeans 2011), and grid-tied and off-grid PV systems appear in the *Electrical Cost Estimating, Green Building: Project Planning and Cost Estimating,* and the *Green Building Cost Data* books, for example (RS Means 2011).

Consider an example of estimating the cost of a direct-gain passive solar heating system. Say we wish to achieve a window area of $A_c = 4\ \text{m}^2$ (45 ft^2) by putting three windows side by side, each window 3 feet wide and 5 feet tall. Table 6-8 lists the hardware and the installation cost for each component.. This information is obtained from cost-estimating manuals (RSMeans 2011), by searching for products for sale on-line, and by contacting suppliers.

In this example our high performance window cost about \$112/ft^2 installed. This may be compared to other types of passive solar heating assemblies from the same reference and shown in Table 6-9.

TABLE 6-8. EXAMPLE COST ESTIMATE FOR 4 m^2 (45 ft^2) WINDOW FOR DIRECT SOLAR HEAT GAIN

	Number of Units	Unit	Material Cost per unit ($/unit)	Labor Cost per Unit($)	Equipment Rental Cost per unit ($)	Total
Windows: 3ft × 5 ft; triple-pane, low-e, argon fill, selective glass, wood frame	3	Each	$390	$118		$1,524
Wood framing for headers 2in × 8in;	2	Each	13.2	51.7		$130
Rigid foam insulation for header and sill blocking	1	Each	$75	51.7		$127
Exterior window sill, metal wrapped wood; 8 inch deep; 9 ft long	1	Each	$150	$84		$234
Aluminum flashing 0.013 inch thick	9	Ft	3.33	13.98		$156

	Number of Units	Unit	Material Cost per unit ($/unit)	Labor Cost per Unit($)	Equipment Rental Cost per unit ($)	Total
Frame lumber for sill blocking 2in × 4in; 9 ft long	2	Each	7.9	40.3		$96
Interior and exterior stop and trim	56	ft	0.24	2		$125
Exterior metal casing metal wrap wood	28	ft	2	2.5		$126
Interior wood casing	28	ft	1	2.5		$98
Valence for shade	10	ft	10.6	26.4		$370
Roller shade	45	ft^2	10	1		$495
Fixed costs						$500
Overhead						$398
Profit						$438
Sales tax						$241
					Total	$5,058
					Average $/ft^2	$112.40

Source: RS Means 2011.

TABLE 6-9. UNIT COSTS ($/m^2, $/ft^2) FOR DIFFERENT TYPES OF PASSIVE SOLAR ASSEMBLIES, EACH BASED ON THE COLLECTOR AREA A_C

Type of Passive Solar System	Unit Cost ($/m^2)	Unit Cost ($/ft^2)
Direct gain	$1,205	$112
Thermal storage wall	$1,680	$156
Sunspace	$1,741	$162

Source: RS Means 2011.

ESTIMATING ENERGY USE AND SOLAR FRACTION

Building Energy Model

Passive solar heating is generally not added to existing buildings, but rather built into new buildings. Modeling is often used to predict loads before a building is built or before a major renovation. An easy-to-use building energy modeling tool is EQuest (Hirsch 2009). The most sophisticated modeling tools used by consultants include Energy Plus and IES VE (EERE 2011). Still there are simple hand calculations that are useful and that can enhance our understanding even better than computer programs can.

Calculate Loads

Above we've described how to calculate the loss coefficient, UA, of a building's envelope and how to add infiltration and internal heat gain to the net heating load calculation. Let us assume that everything affecting heat loss is constant over a day so that we can simplify the integral to a simple equation

$$E_{\text{heat,day}} = [(UA)(T_{\text{room}} - T_{\text{ambient}}) - P_{\text{internal}}] * \left(24\frac{\text{hours}}{\text{day}}\right) \qquad (6\text{-}31)$$

And the fuel consumed by the heater in providing this much energy without any solar input would be

$$E_{\text{fuel}} = \frac{E_{\text{heat}}}{\eta_{\text{heater}}} \qquad (6\text{-}32)$$

CALCULATION OF SOLAR SPACE HEATING SYSTEM SIZING AND ENERGY DELIVERY

The sizes of the major components (window area, mass) of a passive solar system are best determined by optimizing life cycle cost, and satisfying other constraints, using a computer program that takes into account the climate and details of the design. However, we must estimate at least a preliminary size before a design is created, and this may be accomplished by simple hand calculation. If our objective is to offset all of the heating requirements (solar fraction SF = 1), then the collector area may be sized such that the average daily solar resource be equal to the average heating load.

$$E_{\text{solar,day}} = E_{\text{heat,day}} \qquad (6\text{-}33)$$

The month with the greatest heating degree days, $HDD_{\text{day,max}}$ (the coldest month, usually January or December in the Northern Hemisphere and June or July in the Southern Hemisphere) is chosen to make this balance. HDD_{month} has units of Cdays/month or Fdays/month. The daily solar resource coincident with this maximum heating load is $I_{c,\text{min,day}}$. This is the solar energy incident on the plane of the collector (usually a vertical window facing toward the equator) corresponding to the same month as the HDD is maximum. Both $HDD_{\text{month,max}}$ and $I_{c,\text{min,day}}$ are listed in table 6-10 for many US locations and table 6-11 for many international locations.

$$A_c = \frac{\left[(UA) * (HDD_{\text{month,max}}) \,/\left(\frac{31\text{days}}{\text{month}}\right) - P_{\text{internal}} * 24\text{ hour/day}\right]}{KI_{c,\text{min,day}}SHGC} \tag{6-34}$$

Figure 6-13 is a diagram that simplifies how we may think of the coincidence of solar heat gain and heat loss from a building. We have adopted previously the convention that full sun is at a value of 1 kW/m^2, allowing us to calculate a “sunhours” per day by dividing $E_{\text{solar,day}}$ by 1 kW/m^2. We would like for the temperature in the space to be uniform, but if we can tolerate a $\Delta T_{\text{storage}}$, of, say, 4C (8F), we can determine the amount of mass that would be required to store the daily solar resource.

$$M_{\text{storage}} = \frac{A_cKI_{c,\text{min,day}}SHGC - [UA(T_{\text{room}} - T_{\text{ambient}}) - P_{\text{internal}}] * \text{sunhours}}{C_{p,\text{storage}}\Delta T_{\text{storage}}} \tag{6-35}$$

Annual Energy Savings

Daily solar insolation (kWh/m^2/day) on a vertical wall facing toward the equator does not vary much throughout the year, because the position of the sun lower in the sky compensates for the declination. By considering the solar radiation value corresponding to the coldest month, we can be fairly certain that as much sun will be available on other months as well. So the $E_{\text{solar,day}}$ that we calculate above will be available on each average day and what matters to our savings is how much of that heat we can use. This can be evaluated hourly by a computer program, but in this simple hand calculation we perform the comparison for an average day of each month. In any month, the amount of energy saved by the passive solar heating system directly during the day would be the minimum of the available solar energy and the load

$$E_{\text{saved daytime}} = \text{sunhours} * MIN\left[A_cKSHGC * \left(\frac{1kw}{m^2}\right),\; UA(T_{\text{room}} - T_{\text{ambient}}) - P_{\text{internal}}\right] \tag{6-36}$$

Energy put into storage on an average day would be the minimum of solar energy available in excess of the daytime load and the limit imposed by a maximum temperature excursion, $\Delta T_{\text{storage,}}$ of the mass within the space.

$$E_{\text{into storage}} = MIN\left[\left(\text{sunhours} * (A_cK\ SHGC * \left(\frac{1kw}{m2}\right) - UA(T_{\text{room}} - T_{\text{ambient}}) - P_{\text{internal}}),\; M_{\text{storage}}C_{\text{storage}}\Delta T_{\text{storage}} + \lambda_{\text{storage}}\right)\right] \tag{6-37}$$

The solar energy delivered from storage to the heating requirement at night is the minimum of heat saved in storage and the nighttime load.

$$E_{\text{saved nighttime}} = MIN\ [(E_{\text{into storage}}),\ (UA(T_{\text{room}} - T_{\text{ambient}}) - P_{\text{internal}}) * (24 - \text{sunhours})] \tag{6-38}$$

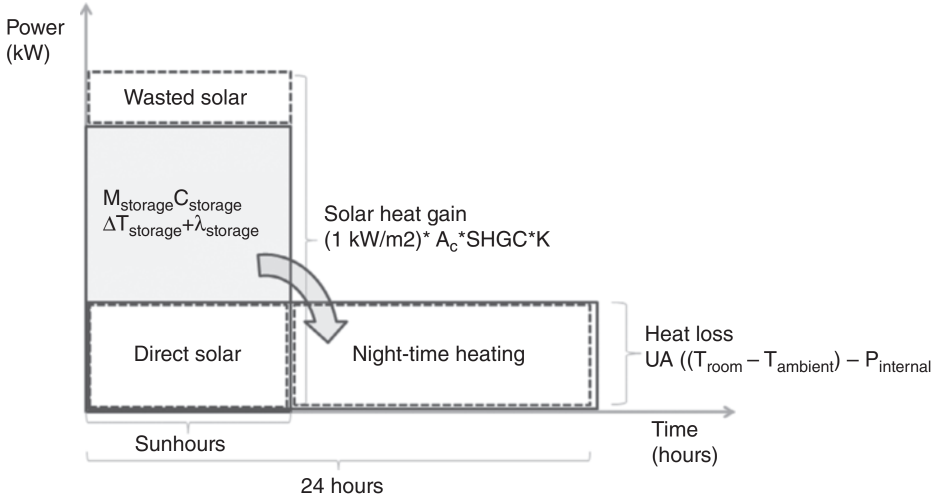


Figure 6-13. The amount of thermal storage (mass, capacitance, and phase change) determines the amount of solar energy that can be stored to serve the load at night. During the day, some of the solar power coming into the space offsets coincident heat loss, some goes into the mass, and the rest is wasted. At night, the solar heat is recovered from the mass. (Figure by the author)

The amount of solar heat ultimately delivered to offset the heating requirement of the space would be the sum of that delivered during the day and through storage at night. The amount of fuel saved would be this solar delivery divided by the efficiency of the heating system.

$$E_{\text{Fuel Savings}} = \frac{(E_{\text{saved daytime}} + E_{\text{saved nighttime}})}{\eta_{\text{heater}}} \qquad (6\text{-}39)$$

Where $E_{\text{fuel Savings}}$ is annual fuel energy savings (kWh/yr) and η_{heater} is the thermal efficiency of the fuel-fired or electric conventional heater. This calculation would be repeated for the 12 months of the year and the results summed to estimate annual energy savings, or as a quick approximation multiply the monthly fuel savings from the coldest month by the number of months that such a heating load persists, which may be approximated by dividing the annual HDD (Cdays/year) by the monthly HDD (Cdays/month) of the coldest month. This number of months varies from zero months in tropical climates to three months at most midlatitude (20 to 40 latitude) climates; four months in cooler climates (40 to 50 latitude) and to seven months or higher in the far northern Arctic.

So with this simple treatment, the two pieces of information that we need to size the passive solar heating components (A_c and $(MC)_{\text{storage}}$) are the heating degree days for the coldest month of the year (C days/month) and the solar insolation on a vertical surface facing toward the equator, $I_{c,\text{day, min}}$ (kWh/m^2/day), corresponding to that coldest month. These two parameters are listed in Table 6-10 for for many locations in the United States and in Table 6-11 for many other locations around the world. To calculate the savings of a highly reflective roof, we need cooling degree days for the hottest month of the year (C days/month) and the solar insolation on a horizontal surface facing upward, $I_{c,b=0,\text{day, max}}$ (kWh/m^2/day), corresponding to that hottest month. This information for calculations related to saving solar-induced air conditioning loads are also listed in tables 6-10 and 6-11.

TABLE 6-10. DATA FOR PASSIVE SOLAR HEATING AND COOLING AVOIDANCE CALCULATIONS. $I_{\beta=90,\text{MIN}}$ (kWh/m^2/day) IS AVERAGE DAILY SOLAR INSOLATION ON A VERTICAL SURFACE FACING SOUTH AVERAGED OVER THE MONTH WITH THE HIGHEST HEATING DEGREE DAYS, $\text{HDD}_{\text{MONTHLY, MAX}}$ (Cdays/month) FOR THE SITE. ($I_{C,\beta=0,\text{MAX}}$ (kWh/m^2/day) IS THE DAILY SOLAR INSOLATION ON A HORIZONTAL SURFACE AVERAGED OVER THE MONTH WITH THE HIGHEST COOLING DEGREE DAYS, $\text{CDD}_{\text{MONTH,MAX}}$ FOR CITIES IN THE US, BY STATE)

State	City	Latitude	$I_{C,\beta=90,\ \min}$ (kWh/m^2/day)	$I_{C,\beta=0,\ \max}$ (kWh/m^2/day)	$\text{HDD}_{\text{month,max}}$ (Cdays/month)	$\text{CDD}_{\text{month,max}}$ (Cdays/month)
Alabama	Huntsville	34.7	3.2	6.1	451	241
Alaska	Anchorage	61.2	1.0	4.9	863	0
	Juneau	58.3	2.5	5.2	819	0
Arizona	Chandler	33.3	3.0	7.0	336	289
	Flagstaff	35.1	5.3	6.4	625	39
	Mesa	33.4	3.0	6.9	336	289
	Phoenix	33.4	4.9	7.6	201	491
	Scottsdale	33.5	3.2	6.9	336	289
	Tucson	32.1	5.2	7.1	236	372
California	Bakersfield	35.4	3.0	8.0	302	329
	Chula Vista	32.6	3.3	6.1	127	143
	Fresno	36.8	2.6	8.0	338	291
	Inyokern	35.6	3.4	7.4	399	262
	Lancaster	34.7	3.5	6.9	266	242
	Long Beach	33.8	4.1	6.7	158	164
	Modesto	37.6	3.5	8.0	322	140
	Ontario	34.1	3.2	6.6	314	277
	Oxnard	34.2	3.2	6.6	204	151
	Palmdale	34.6	3.7	6.9	266	242
	Riverside	34.0	2.9	6.5	210	263
	Sacramento	38.5	2.7	7.9	341	184

(continued)

TABLE 6-10. ***(Continued)***

State	City	Latitude	$I_{C,\beta=90}$, min (kWh/m^2/day)	$I_{C,\beta=0}$, max (kWh/m^2/day)	HDD$_{\text{month,max}}$ (Cdays/month)	CDD$_{\text{month,max}}$ (Cdays/month)
	San Diego	32.7	4.5	6.5	136	133
	San Francisco	37.6	3.3	5.4	281	36
	Santa Rosa	38.4	3.3	7.4	252	198
	Stockton	38.0	3.5	7.4	237	123
	Truckee	39.3	3.5	8.2	484	114
Colorado	Alamosa	37.5	5.7	7.2	866	22
	Denver	39.7	3.0	6.4	640	83
	Eagle	39.7	4.4	6.1	797	42
	Fort Collins	40.6	3.3	6.4	727	57
	La Junta	38.0	3.3	6.7	556	127
Connecticut	Hartford	41.9	3.3	5.9	696	150
Delaware	Wilmington	39.7	3.4	6.1	592	196
Florida	Fort Lauderdale	26.1	2.5	5.1	26	268
	Jacksonville	30.5	3.8	5.8	234	286
	Key West	24.6	4.3	6.1	24	334
	Miami	25.8	4.1	5.6	49	307
	Orlando	28.5	2.4	5.4	99	266
	Tampa	28.0	4.0	5.8	130	294
Georgia	Atlanta	33.7	3.5	6.2	412	238
Hawaii	Hilo	19.7	3.8	5.3	0	194
	Honolulu	21.3	4.3	6.5	0	282
Idaho	Boise	43.6	2.7	7.6	620	158
Illinois	Aurora	41.8	2.8	6.1	727	201
	Chicago	41.8	3.1	6.1	758	144
	Joliet	41.5	2.9	6.1	727	201
Indiana	Fort Wayne	41.0	2.8	6.1	725	155
Kansas	Overland Park	39.0	3.0	6.3	617	237
	Wichita	37.7	4.1	6.8	612	282
Kentucky	Lexington-Fayette	38.0	2.9	6.0	589	186
Louisiana	New Orleans	30.0	3.3	5.7	250	291
	Shreveport	32.5	3.4	6.4	346	305
Maine	Bangor	44.8	2.8	5.3	797	105
Maryland	Baltimore	39.2	3.4	6.0	572	207
Massachusetts	Boston	42.4	3.4	6.1	627	147
Michigan	Detroit	42.4	2.6	6.1	725	128
	Houghton	47.2	2.4	6.0	828	62
Minnesota	Duluth	46.8	3.4	6.1	999	52
Mississippi	Natchez	31.6	2.5	5.9	278	280
Montana	Billings	45.8	3.4	7.0	727	136
	Kalispell	48.3	2.1	5.6	767	35
Missouri	St. Louis	38.8	3.5	6.4	615	255
Nebraska	Lincoln	40.8	3.0	6.4	709	193
	Omaha	41.4	3.9	6.6	767	198

State	City	Latitude	$I_{C,\beta=90,\ \min}$ (kWh/m^2/day)	$I_{C,\beta=0,\ \max}$ (kWh/m^2/day)	HDD$_{\text{month,max}}$ (Cdays/month)	CDD$_{\text{month,max}}$ (Cdays/month)
Nevada	Las Vegas	36.1	5.0	7.9	336	449
	Reno	39.5	4.0	7.8	556	121
New Hampshire	Concord	43.2	3.7	6.1	799	85
New Jersey	Newark	40.7	3.3	5.9	592	221
New Mexico	Albuquerque	35.1	5.2	7.5	531	233
	Las Cruces	32.3	3.1	6.5	456	191
New York	Albany	42.8	3.1	6.1	764	118
	Buffalo	42.9	2.4	6.0	713	108
	New York	40.8	3.2	6.0	577	203
North Carolina	Charlotte	35.2	3.6	6.1	443	246
	Greensboro	36.1	3.7	6.1	487	205
	Raleigh	35.9	3.6	6.1	449	226
North Dakota	Fargo	46.9	3.5	6.4	1018	116
Ohio	Columbus	40.0	2.6	5.9	665	143
Oklahoma	Oklahoma City	35.4	4.3	6.9	501	293
Oregon	Portland	45.6	1.8	5.4	437	82
	Salem	44.9	1.9	5.7	437	58
Pennsylvania	Philadelphia	39.9	3.3	6.0	596	202
Rhode Island	Providence	41.7	3.4	5.9	639	133
South Carolina	Columbia	34.0	3.6	6.1	369	272
South Dakota	Sioux Falls	43.6	3.7	6.6	882	166
Tennessee	Memphis	35.1	3.5	6.5	436	303
Texas	Amarillo	35.2	4.8	7.0	515	234
	Arlington	32.7	3.1	5.8	356	289
	Brownsville	25.9	3.0	6.5	129	336
	Dallas/Fort Worth	32.8	4.0	7.0	372	349
	El Paso	31.8	5.1	7.4	382	298
	Houston	30.0	3.1	5.9	260	303
	Laredo	27.5	2.8	6.7	161	266
	Lubbock	33.7	4.7	7.0	451	258
	San Antonio	29.5	3.8	6.9	274	344
Utah	Salt Lake City	40.8	3.2	7.3	639	222
	Provo	40.2	3.5	7.1	805	94
Vermont	Burlington	44.5	1.6	5.4	868	91
Virginia	Chesapeake	36.8	2.8	5.7	409	257
	Norfolk	36.9	3.4	5.9	446	227
	Richmond	37.5	3.5	6.0	504	224
Washington	Seattle	47.5	1.5	5.2	429	45
	Yakima	46.6	2.5	7.2	608	95
West Virginia	Huntington	38.4	1.8	5.6	561	188
Wisconsin	Madison	43.1	3.5	6.2	844	110
Wyoming	Cheyenne	41.2	4.2	6.7	663	76

Source: NASA LARC 2012, Marion and Wilcox 1994, and Minister of Natural Resources Canada, 2012. Data processed by Josh Walker.

TABLE 6-11. DATA FOR PASSIVE SOLAR HEATING AND COOLING AVOIDANCE CALCULATIONS. $I_{\beta=90,\text{MIN}}$ (kWh/m^2/day) IS AVERAGE DAILY SOLAR INSOLATION ON A VERTICAL SURFACE FACING TOWARD THE EQUATOR AVERAGED OVER THE MONTH WITH THE HIGHEST HEATING DEGREE DAYS, HDD$_{\text{MONTHLY,MAX}}$ (Cdays/month) FOR THE LOCATION. $I_{C,\beta=0,\text{MAX}}$ (kWh/m^2/day) IS THE DAILY SOLAR INSOLATION ON A HORIZONTAL SURFACE AVERAGED OVER THE MONTH WITH THE HIGHEST COOLING DEGREE DAYS, CDD$_{\text{MONTH,MAX}}$; FOR CITIES IN VARIOUS COUNTRIES, BY COUNTRY

Country	City	Latitude	$I_{C,\beta=90,\text{ min}}$ (kWh/m^2/day)	$I_{C,\beta=0,\text{ max}}$ (kWh/m^2/day)	HDD$_{\text{month,max}}$ (Cdays/month)	CDD$_{\text{month,max}}$ (Cdays/month)
Afghanistan	Kabul	34.5	4.7	7.7	662	347
Albania	Tirana	41.3	3.2	7.2	341	459
Algeria	Algiers	36.8	3.1	6.4	180	471
Angola	Luanda	–8.9	2.9	5.4	0	577
Argentina	Buenos Aires	–34.6	0.7	6.9	217	450
	Mendoza	–32.8	0.7	7.4	301	481
	Ushuaia	–54.8	0.5	5.0	499	0
Australia	Adelaide	–34.9	0.6	7.4	211	375
	Alice Springs	–23.8	1.0	7.6	189	611
	Canberra	–35.3	0.7	7.4	384	313
Austria	Vienna	48.1	2.2	5.2	567	326
Azerbaijan	Baku	10.4	3.0	5.0	406	462
Bahamas	Nassau	25.1	4.3	6.4	0	577
Bangladesh	Chittagong	22.3	4.6	4.0	0	535
	Dhaka	23.7	4.3	4.7	0	547
Belarus	Minsk	53.9	1.3	5.0	772	226
Belgium	Antwerp	51.2	1.6	4.8	450	267
Belize	San Ignacio	17.2	3.5	5.3	0	490
Bhutan	Samtse	27.3	4.7	4.9	515	149
Bolivia	Santa Cruz	–17.8	1.1	5.6	0	499
Bosnia	Sarajevo	43.8	2.0	5.8	586	276
Brazil	Rio de Janeiro	–22.9	1.0	5.2	0	502
	Brasília	–11.0	1.2	5.2	0	593
Canada	Edmonton	53.3	2.9	5.8	893	236
	Montreal	45.5	5.2	4.8	465	299
	Saskatoon	52.2	1.3	6.5	1101	267
	Toronto	43.7	2.6	6.0	776	326
	Vancouver	49.2	2.4	5.2	465	229
	Winnipeg	49.9	1.4	6.3	1125	304
	Yellowknife	62.5	2.4	5.7	1423	202
Chile	Punta Arenas	–53.0	0.2	5.5	524	16
	Santiago	–33.5	0.6	6.5	307	338

Country	City	Latitude	$I_{C,\beta=90,\ \min}$ (kWh/m^2/day)	$I_{C,\beta=0,\ \max}$ (kWh/m^2/day)	HDD$_{\text{month,max}}$ (Cdays/month)	CDD$_{\text{month,max}}$ (Cdays/month)
China	Baotou Neimongol	40.6	5.9	6.0	1109	362
	Beihai Guangxi	21.5	2.4	4.9	96	589
	Beijing	39.9	4.0	4.6	691	493
	Changsha Hunan	28.2	1.5	5.0	400	592
	Chengdu Sichuan	30.7	1.3	5.6	388	471
	Chungking	29.6	1.3	3.9	313	567
	Fuzhou Fujian	26.1	1.7	5.3	211	592
	Guangdong Tianjin	22.3	5.2	5.1	640	501
	Ganzhou Jiangxi	25.9	2.2	5.3	298	605
	Guiyang, Guizhou	26.6	1.2	3.1	406	425
	Haikou Hainan	20.0	2.7	5.5	0	589
	Harbin Heilongjiang	45.8	3.2	5.1	1107	403
	Hefei Anhui	31.9	2.5	3.3	468	567
	Hong Kong	22.3	2.9	5.3	40	601
	Jilin Jilin	43.9	5.3	4.8	1037	353
	Jinzhou Liaoning	41.1	4.2	4.4	791	450
	Kunming Yunan	25.0	3.7	3.9	285	310
	Lanzhou Gansu	36.1	3.1	5.5	698	397
	Lhasa Tibet					
	Tsingtao Shandong	36.1	2.6	3.8	564	489
	Shanghai	31.4	2.0	4.8	406	570
	Shenzhen Guangdong	22.6	2.9	5.0	78	589
	Shijiazhuang Hebei	38.0	5.0	4.9	605	533
	Suzhou Jiangsu	31.3	3.1	5.0	438	499
	Urumqi Xinjiang	43.8	2.6	6.0	936	431
	Wuhan Hubei	30.6	1.7	4.8	428	589
	Xian Shaanxi	34.3	2.6	4.1	549	524
	Xining Qinghai	36.6	4.4	5.4	775	226
	Yanchi Ningxia	37.8	5.8	5.8	787	406
	Zhengzhou Henan	34.7	3.7	4.8	536	527
Colombia	Bogota	4.7	3.3	3.7	158	118
Congo	Kinshasa	–4.3	1.3	4.3	0	469
	Lubumbashi	–11.7	1.3	6.3	0	496

(continued)

TABLE 6-11. ***(Continued)***

Country	City	Latitude	$I_{C,\beta=90,\,\min}$ (kWh/m^2/day)	$I_{C,\beta=0,\,\max}$ (kWh/m^2/day)	HDD$_{\text{month,max}}$ (Cdays/month)	CDD$_{\text{month,max}}$ (Cdays/month)
Cook Islands	Pukapuka	–10.9	1.4	5.0	0	577
Costa Rica	San José	10.0	2.0	6.2	0	397
Côte d'Ivoire	Abidjan	5.3	3.5	4.8	0	552
Cuba	Havana	23.0	4.0	6.1	0	524
Czech Republic	Prague	50.0	1.8	4.8	580	274
Denmark	Copenhagen	55.7	1.1	4.3	529	246
Egypt	Cairo	30.1	3.6	6.7	144	566
Ethiopia	Addis Ababa	9.0	1.5	5.6	93	245
Finland	Helsinki	60.3	0.9	5.5	772	205
France	Marseille	43.5	3.0	7.2	350	453
	Paris	48.8	1.2	4.4	397	329
	Lyon	45.7	1.4	6.3	481	335
Georgia	Tbilisi	41.7	2.2	6.2	505	446
Germany	Frankfurt	50.1	1.6	4.9	515	298
	Hamburg	53.6	1.1	4.8	543	211
	Munich	48.1	2.2	5.3	546	295
Iceland	Reykjavík	64.1	0.9	4.3	555	34
India	Ahmadabad Gujarat	23.1	4.9	7.3	0	741
	Bangalore	13.0	4.5	6.8	0	540
	Bhopal	23.3	4.7	6.5	0	732
	Calcutta	22.5	3.4	6.4	0	642
	Chandigarh	30.8	4.5	7.1	234	575
	Delhi	28.6	4.4	6.3	115	702
	Dhera Dun Uttaranchal	30.3	4.5	6.7	505	257
	Gauhati Assam	26.1	4.9	4.3	37	580
	Goa	15.5	4.9	6.6	0	620
	Hyderabad	17.5	4.3	6.8	0	713
	Itanagar Arunchal	27.1	3.6	4.3	339	305
	Kargil Kashmir	34.6	4.2	6.6	1105	0
	Leh Ladakh	34.2	4.5	6.2	1213	0
	Lucknow Uttar	26.8	4.1	6.6	118	694
	Ludhiana Punjab	30.4	4.4	6.4	219	651
	Madras	13.0	5.0	6.4	0	710
	Manali Himachal	32.3	3.9	6.0	489	0
	Mumbai	19.1	4.3	6.7	0	626
	Patna Bihar	25.6	4.6	6.9	87	667
	Poona	18.5	4.7	7.1	0	611
	Shrinagar Kashmir	34.1	2.3	6.8	481	437
	Trivandrum	8.5	4.2	5.9	0	574

Country	City	Latitude	$I_{C,\beta=90,\,min}$ (kWh/m^2/day)	$I_{C,\beta=0,\,max}$ (kWh/m^2/day)	$HDD_{month,max}$ (Cdays/month)	$CDD_{month,max}$ (Cdays/month)
Indonesia	Jakarta	–6.3	2.0	4.3	0	558
	Palembang	–3.0	2.4	4.7	0	487
Iran	Shiraz	29.5	4.0	7.4	378	583
	Tabriz	38.1	3.1	7.6	642	502
	Tehran	35.7	3.2	7.5	465	632
Iraq	Baghdad	33.2	4.0	7.2	255	811
	Mosul	36.3	2.5	6.2	454	655
Ireland	Dublin	53.4	1.3	4.7	391	167
Israel	Haifa	32.8	3.3	6.9	149	552
Italy	Milan	45.4	1.5	6.0	484	453
	Palermo	38.2	3.3	6.9	171	524
	Venice	45.5	1.5	5.8	468	431
Japan	Akita	39.7	1.5	4.7	570	446
	Nagasaki	32.7	2.5	5.8	468	431
	Sapporo	43.1	3.1	4.3	701	363
	Tokyo	35.7	2.7	3.4	397	530
	Yamagata	38.3	2.4	4.1	570	462
Kazakhstan	Karaganda	49.8	2.9	6.1	958	322
Kenya	Nairobi	–1.3	3.8	6.4	74	291
Korea, N.	Pyongyang	38.4	4.9	3.9	794	394
Korea, S.	Seoul	37.6	2.9	3.6	663	477
Korea, S.	Suwon	37.3	4.7	4.2	642	481
Kuwait	Kuwait City	29.2	3.5	7.5	171	859
Kyrgyzstan	Osh	40.5	3.8	7.4	608	496
Latvia	Riga	57.0	1.1	5.2	704	214
Lebanon	Beirut	33.8	2.6	6.3	146	515
Macedonia	Skopje	45.0	2.2	6.7	564	425
Madagascar	Antananarivo	–18.8	1.1	5.2	121	326
Malaysia	Kuala Lumpur	3.1	2.5	4.6	0	533
Mali	Bamako	12.5	3.0	6.4	0	675
Mexico	Chihuahua	28.6	5.3	7.3	179	500
	Merida	21.0	4.0	6.3	0	586
	Mexico City	19.4	4.1	5.6	127	285
	Monterey	25.7	4.2	6.1	84	589
Mongolia	Ulan Bator	47.9	3.9	5.3	1321	205
Morocco	Casablanca	33.6	3.4	5.9	161	394
Mozambique	Maputo	–25.9	0.9	6.8	0	512
Myanmar	Mandalay	22.0	3.2	6.4	0	518
	Yangon	16.8	4.7	6.5	0	557
Nepal	Kathmandu	27.7	5.1	4.8	334	299
Netherlands	Amsterdam	52.3	1.6	5.4	456	233
New Zealand	Auckland	–37.0	0.7	6.6	233	295

(continued)

TABLE 6-11. ***(Continued)***

Country	City	Latitude	$I_{C,\beta=90,\ \min}$ (kWh/m^2/day)	$I_{C,\beta=0,\ \max}$ (kWh/m^2/day)	HDD$_{\text{month,max}}$ (Cdays/month)	CDD$_{\text{month,max}}$ (Cdays/month)
Nicaragua	Managua	12.2	4.5	5.8	0	583
Nigeria	Lagos	6.5	3.6	5.5	0	511
Norway	Oslo	60.2	1.3	5.3	722	192
Pakistan	Faisalabad	31.4	4.1	6.7	212	726
	Gujranwala	32.2	4.1	7.5	290	577
	Hyderabad	25.4	3.9	6.9	12	668
	Karachi	24.9	4.7	6.4	0	642
	Lahore	31.5	3.3	34.5	161	717
	Multan	30.2	4.0	6.5	164	765
	Peshawar	34.0	4.2	7.2	211	693
	Quetta	30.2	4.2	7	445	555
Paraguay	Asunción	–25.3	0.9	6.1	12	543
Peru	Lima	–12.0	3.6	7.1	37	394
Philippines	Davao	7.1	3.0	5.4	0	561
Poland	Warsaw	52.2	1.2	5.1	660	248
Russia	Grozny Chechnya	43.4	2.9	5.9	611	425
	Moscow	55.8	1.5	5.1	896	254
Saudi Arabia	Jidda	21.7	4.5	7.0	0	698
Senegal	Dakar	14.7	4.1	5.5	0	546
Somalia	Mogadishu	2.0	4.6	6.5	0	567
South Africa	Cape Town	–34.0	0.7	7.7	189	322
	Pretoria	–25.9	4.5	6.8	211	332
Spain	Barcelona	41.4	3.5	5.8	268	409
	Seville	37.4	3.9	6.5	226	524
Sweden	Linkoping	58.4	1.5	5.3	583	217
Switzerland	Geneva	46.3	1.4	5.9	508	322
Syria	Aleppo	36.2	3.1	7.6	372	583
Taiwan	Taipei	25.0	1.8	4.7	59	605
Tajikistan	Dushanbe	38.6	3.0	7.4	450	585
Tanzania	Dar es Salaam	-6.9	1.4	5.3	0	546
Thailand	Bangkok	13.7	1.8	5.7	0	591
Tunisia	Sidi Bou Said	35.0	3.1	7.4	242	605
Turkey	Antalya	36.9	2.7	7.2	257	570
	Bursa	40.2	2.3	6.8	397	440
	Istanbul	41.1	2.0	6.3	370	412
Uganda	Kampala	0.3	1.9	5.4	0	370
Ukraine	Odessa	46.4	1.4	6.2	611	357
United Kingdom	Edinburgh	56.0	1.6	4.3	437	152
	Leeds	53.8	1.4	4.5	400	211
	London	51.5	1.1	4.5	378	270
Venezuela	Caracas	10.6	3.6	5.7	0	549
Virgin Islands	Charlotte Amalie	18.4	4.7	6.4	0	518
Yemen	Sana'a	15.5	3.3	5.3	16	518

Source: NASA LARC 2012, Marion and Wilcox 1994, Minister of Natural Resources Canada, 2012. Data processed by Josh Walker.

Estimating the Energy Cost Savings of a Passive Solar Heating System

You can't save more than you use, and excess solar heat is wasted in months other than the coldest month, but we have already taken that into account in the estimate of fuel savings above, so we assume all of the calculated solar energy savings displaces a unit cost of energy ($/kWh). The annual cost of operating and maintaining the solar water heating system $C_{O\&M}$ ($/year), is subtracted to estimate annual cost savings

$$C_{savings} = E_{fuel\ savings}C_{fuel,retail} - C_{O\&M} \tag{6-40}$$

Where $C_{savings}$ is annual cost savings ($); $c_{elec,\ retail}$ is the unit cost of electricity ($/kWh) representative of what the utility charges you for energy. This may be in addition to other charges on your bill such as fuel delivery, peak demand charges, and fixed charges that the solar system does not reduce the cost of. Unlike solar electricity, there is no useful value to the solar heat in excess of the load.

LIFE CYCLE COST ANALYSIS OF PASSIVE SOLAR HEATING SYSTEM

It is often difficult to separate the cost of a passive solar heating feature, such as a window, from the price of conventional construction. Many passive solar buildings report costs that are equivalent or even lower than conventional construction. Indeed, there is much evidence that you don't need passive solar to have an expensive building.

Similarly, it is often difficult to separate out the performance of the passive solar heating system from other aspects of the building envelope and mechanical system performance.

To the extent, however, that a decision can be isolated, a simple economic model is adequate to inform decisions based on life cycle cost. Simple models are required because decisions are made early in the design process before the details are available that a more sophisticated analysis would require. The life-cycle cost, LCC, of the basecase is the annual heating bill times the present worth factor. The LCC of the solar case is the initial cost of implementing the solar system plus the same present worth factor times the heating bill as reduced by the solar heat delivery. The increased operation and maintenance costs associated with the solar energy systems is also multiplied by the present worth factor and added to the life-cycle cost.

The difference between $LCC_{Basecase}$ and LCC_{PVCase} is the net present value of the life-cycle savings, LCS, of a project and is approximated by

$$LCS = (C_{savings})\ \text{PWF}\ (d,\ N) - C_{initial}) \tag{6-41}$$

Where the present worth factor, $PWF(d,N)$, is the factor to discount at the rate of d percent per year a stream of N annual cash flows down to their present value. For example, the PWF for $N = 25$ years of cash flows at $d = 3$ percent discount rate is 17.4 years. The PWF has units of years, but it reflects that the value of $1/year for 25 years is worth only $17.4 today.

Another useful metric is the savings to investment ratio, or SIR, which is the ratio of life cycle savings to the investment.

$$SIR = \frac{C_{savings}PWF(d,N)}{C_{initial}} \tag{6-42}$$

An SIR of greater than one (SIR > 1) indicates that a project is cost effective. Size of a Passive Solar Heating system, initial cost, annual energy delivery, annual cost savings, and life-cycle cost may be estimated by this simple hand calculation, but subsequently more detailed analysis using computer tools must be used to refine the estimate of economic savings.

Example Calculation of Size, Cost, and Heating Energy Saving of a Passive Solar Heating System

In this example, we consider a passive solar heating system for a small two-story commercial building in Chicago of 1,000 m^2 (10,000 ft^2) floor area. Each floor would thus have 500 m^2 (5,000 ft^2) of floor area. The building envelope is to be constructed of structural insulated panels (SIPs) composed of two sheets of oriented strand board sandwiching rigid polyurethane foam insulation with an effective R-value of R = 3.3 m^2C/W (R19 ft^2hrF/Btu). The roof is also SIP but rated for R = 4.2 m^2C/W (R24 ft^2hrF/Btu). The windows have a U-value of 1.36 W/m^2/C (0.24 Btu/ft^2/hr/F) and a solar heat gain coefficient (SHGC) of = 0.60.

Say the building is to be heated with electric resistance baseboard heaters at a cost of $0.16/kWh. As a hedge against increasing fuel costs, the building owner directs the designer to offset the calculated heating load with passive solar heat gain. The internal heat gain is estimated at 2kW for lights and computers. Consider infiltration of air at a rate of 0.4 air changes per hour, and for the properties of air take density $\rho = 1.2475$ kg/m^3 (0.078 lbm/ft^3) and specific heat $c_p = 1.00$ kJ/kgK (240.4 Btu/lbmF). Say this building is heated 24 hours a day and 7 days a week, such as an all-night convenience store might be, so the internal heat gain is continuous and there is a need for building heating each day.

Estimate the size (m^2, ft^2) of the passive solar heating collector, the mass of concrete that would be required for thermal storage, and the associated cost of the passive solar system. Will the solar collectors (windows) fit on the south side of the building? Estimate monthly average daily energy delivery in the winter month when heating degree days are a maximum. Estimate life-cycle cost effectiveness of the system. For thermal storage consider concrete with a specific heat of $cp = 840$ J/kg/K. For the life-cycle cost analysis assume a 3 percent discount rate and a 25-year analysis period, so the present-worth factor is 17.4 years.

In a cold climate a compact floor plan is generally desirable, but in order to respond to the sun's path across the sky, we expand the south side and contract the east and west sides. We wish to follow Frank Lloyd Wright's advice that the floor plate should not exceed 45 feet (14 m) in order to allow for effective daylighting and natural ventilation, so a building length of 111 ft (34 m) results, with the long axis running east-west.

Thus the total surface area of the building is 8,729 ft^2. In this simple example let's neglect heat loss to the ground. The roof area is 5,000 ft^2 (464 m^2). If we initially guess that the window area might cover half of the south wall, the window area would be 1,332 ft^2 (124 m^2), and the remaining wall area would be 6,156 ft^2 (572 m^2). Referring to the table of solar resource data above, we find Chicago and the month with the greatest heating degree days is January with HDD_{month} = 758 Cdays/month. In this same month the value of $I_{c,\beta=90,\text{min}}$ is 2.4 kWh/m^2/day (NASA LARC 2012; Marion and Wilcox 1994). Annual heating degree days are 3,631 C days, which indicates that the heating season persists for about five months. In this example we neglect the effect of the incident angle modifier, K, which would be taken into account in a computer simulation. Also, we calculate the balance between heat loss and solar heat gain as daily averages, and it would be more accurate to estimate heat flows hourly with a computer simulation.

Table 6-12 lists calculation of the heat transfer coefficients and the size of the windows according to equation 6-34, the size of the storage from equation 6-35, and the annual energy delivery according to equation 6-39. Economic parameters are also presented.

We estimate that a system size of A_c = 214 m^2 (2,302 ft^2) would provide enough heat to offset our heating load on an average day during the coldest month of the year. This would indeed fit within the 247 m^2 (2,664 ft^2) south-facing wall area. The mass required to store that amount of energy from day to night, assuming it is in the form of the concrete floors, is 569,978 kg (1,253,951 lbs). Using a concrete density of 2100 kg/m^3, this amount of mass could be provided in a concrete slab floor 9 cm (4 inches) thick throughout the entire building. Both the glazing area and the mass could fit within the dimensions of the building.

Annual utility cost savings are estimated at $9,445/year, which entails a simple payback period of 38 years to return the $359,134 initial cost. Considering the long life of a building, 38 years might not sound too bad, but since we are considering a 25-year analysis period, the project is not cost effective as indicated by an SIR of less than 1.0. Cost-effectiveness of solar space heating is challenged by the fact that the solar

TABLE 6-12. EXAMPLE CALCULATIONS OF THE SIZE, ANNUAL ENERGY DELIVERY, COST, AND COST-EFFECTIVENESS OF A PASSIVE SOLAR HEATING SYSTEM

Building parameters			
UA roof	Heat loss coefficient for roof = (5000 ft^2)/(24 ft^{2}Fhr/Btu)	208 Btu/hr/F	110 W/C
UA walls	Heat loss coefficient for walls = (6156 ft^2)/(19 ft^{2}Fhr/Btu)	324 Btu/hr/F	171 W/C
UA windows	Heat loss coefficient for windows = (1,332 ft^2)*(0.24 Btu/ft^2/F/hr)	320 Btu/hr/F	169 W/C
$m_{\text{infiltration}}$	Mass flow rate of infiltration air = (0.4 air changes per hour)*(10000 ft^2)*(12 ft ceiling)*(0.078 lbm/ft^3)	3,744 lbm/hr	1,702 kg/hr
UA	Building loss coefficient $\Sigma UA + m_{\text{infiltration}}C_p$	1,751 Btu/hrF	924 W/C
P_{internal}	Internal heat gain	20,472 Btu/hr	6,000 W
SHGC	Solar heat gain coefficient of window	0.60	
Climate data			
$HDD_{\text{month,max}}$	*HDD* in January Table 6-10	1364.4 F days	758 C days
$I_{c,\beta=90,\text{ min}}$	Solar in plane of windows Table 6-10	983.0 Btu/ft^2/day	3.1 kWh/m^2/day
Calculations			
	Daily heat loss UA*HDDmonth,max/31days/mo*24h/day	1,849 kBtu/day	542 kWh/day
A_c	Collector area UA*$\text{HDD}_{\text{month,max}}$/31days – $\text{P}_{\text{internal}}$*24hr/day/$I_{c,\text{min,day}}$SHGC Equation 6-34	2,302 ft^2	214 m^2

$(T_{room} - T_{ambient})$	average temperature difference = HDD_{month}/ (31days/mo)	44 F	24 C
$M_{storage}$	Thermal storage mass = (A_c KI_(c,min,day) (SHGC)_– [UA(T_room (–T)_ambient) – P_internal]*sunhours)/ (C_(p,storage) ΔT – storage) Equation 6-35	1253951 Lbs	569978 kg
Δt	days that heating load persists = $HDD_{annual}/(T_{room} - T_{ambient})$ = 3,631 C_{days}/24C	148 Days	
$E_{savings\ annual}$	Annual energy savings = $I_c A_c SHGC \Delta t$ Equation 6-39	202 million Btu/year	59095 kWh/year
Economic analysis			
$C_{initial}$	Intial cost = A_c*\$156/ft^2 for thermal storage wall	\$359,134	
$C_{savings}$	Annual cost savings = $E_{savings,annual}$*\$0.16/kWh (Equation 6-40)	\$9,455	
SPB	Simple payback period (years)	38	
LCS	Life – cycle savings = $C_{savings}$*PWF – $C_{initial}$ (Equation 6-41)	–\$194,613	
SIR	Savings to investment ratio = (C_{saving}s*PWF)/$C_{initial}$ (\$9,455/year*17.4 years)/\$359,134 (Equation 6-42)	0.46	
LCOE	Levelized cost of energy = ($C_{initial}$/PWF – $C_{savings}$)/ $E_{savings\ annual}$ (\$359,134/17.4 years – \$9,455/year*)/ (303 million Btu)	\$55.47 \$/million Btu	\$0.19 \$/kWh

resource is a minimum when the heating load is a maximum and by the fact, in this example, that we can only use the solar heat 148 days per year. The rest of the year the solar heat is wasted. Still there might be other reasons to consider passive solar heating on a project such as views and natural light through the windows, hedge against increases in future utility rates, and concerns about environmental emissions from burning fossil fuels on-site.

COMPUTER TOOLS FOR ANALYSIS OF PASSIVE SOLAR SYSTEMS

"Whole building" models are required to evaluate passive solar heating and cooling load avoidance, since those effects are integral to the building construction. Solar heat through a window can be beneficial or detrimental depending on what else is going on—is the building in need of heat or is it already heated by busy people and computers?

It takes a lot of detail to create a building energy model. The problem is one of both thermodynamics and heat transfer. The first law of thermodynamics (conservation of energy) is written for each element of the building, each individual layer of a wall, for example. The "first law" equation for each layer has terms for heat in and heat out based on heat transfer (convection, radiation) and a term for energy stored in the mass by virtue of its temperature. Each layer of a wall assembly has a temperature or a temperature profile associated with it. Thus for each layer that we have, we add one equation (first law) and one unknown (its temperature). We build a system of simultaneous equations. As long as the number of equations equals or exceeds the number of unknowns, we can solve the system of simultaneous equations for the temperature of each layer and all the heat flow terms. Techniques used to solve the system of simultaneous equations include: iteration; matrix inversion, substitution, and Gaussian elimination. Computer tools use iteration or matrix inversion. With mass analogous to capacitance and insulation analogous to resistance, techniques originally designed to solve electrical circuits were initially applied to building energy models. The system of simultaneous equations is solved at a single time step, and then the temperatures calculated at the end of a time step become the starting temperature for the next step. Most programs use a one-hour time step, so the system of simultaneous equations is solved 8,760 times (24 hours*365 days) to simulate one year of performance. Such time series analysis is called "computer simulation." The

EnergyPlus program is the only one that lets the user specify a time step other than one hour. Fifteen minutes is a logical time step since that is the period that most utility companies average demand for billing purposes.

A complete building model may have a very large number of elements: each wall facing off in a different direction; each window and its properties; internal heat gain; infiltration of air and humidity; and solar heat gain on opaque surfaces such as roofs. A further complexity is added when the mechanical system that heat and cool these spaces is modeled: rooms can be organized into mechanical "zones"; zones organized into "systems," and heated and chilled water supplied by "plants." Fortunately, building energy modeling software has evolved to handle this complexity with aplomb.

One of the most exciting developments in building modeling is the ability to import building geometry from CAD data.

A comprehensive list of 406 building software tools and 251 energy analysis tools for researchers, designers, architects, engineers, builders, and code officials can be found at apps1.eere.energy.gov/buildings/tools_directory/.

The first two successful energy models were DOE-2, produced by researchers under Department of Energy support over several years, and BLAST (Building Loads and System Thermodynamics) program by the Department of Defense Civil Engineering Research Laboratory and the University of Illinois at Urbana–Champaign. Another early success in setting up and solving a system of simultaneous equations was SERIRES, by the Solar Energy Research Institute. The many institutions supporting that research have coalesced to produce the more recent EnergyPlus program, and research continues to develop the capabilities of that program and also to develop user-interfaces that are more user-friendly and facilitate delivery of results at a reasonable cost. A comparison of some few computer simulation programs is provided in Table 6-13 based on review of on-line tools directories (DOE OBT 2011), interviews with practioners, and funding agencies, and involvement or experience of the author. This comparison is certainly not inclusive of all programs available and is not intended to indicate that one is any better than another, rather that each has appropriate applications. Where possible I've used the developers own description of their tool. The programs are compared according to the following criteria:

- Nonproprietary: computer program is available to competing commercial interests.
- Calculations may be checked: calculations which are used to generate the results should be visible in a spreadsheet form or well-described in program documentation.
- Climate data: extensive weather data for multiple countries or access to climate data is facilitated.

TABLE 6-13. COMPARISON OF COMPUTER SOFTWARE PROGRAMS FOR DESIGN AND ANALYSIS OF PASSIVE SOLAR HEATING SYSTEM PERFORMANCE

	Nonproprietary	Visible or well-described calculations	Extensive weather data	Well tested	Free or Low Cost	User support	Recently Updated	Documentation
COMFIE				*		*	*	*
DEROB-LTH			*	*				*
DOE-2	*	*	*	*	*			*
Energy Plus	*	*	*	*	*		*	*
Energy Scheming		*		*		*		*
ESP-r	*	*		*	*		*	*
Hot2 XP and HOT2000	*	*		*			*	*
RETScreen	*		*	*	*	*		*
Solacalc		*		*		*		*
SUNREL	*	*		*	*			*
SOLAR-5 (HEED)	*	*		*		*	*	*
TRNSYS		*	*	*	*	*	*	*
Window 4.1	*	*	*	*	*	*	*	*

- Well tested: computer program used on many projects to vet bugs and ensure usefulness and confidence in the results.
- Cost: free or low cost.
- User support: contact information is valid and support and training are available.
- Recently updated: program is reflective of current models and computer systems.
- Documentation: complete reference material is available.

A short description is provided for each tool along with other information, including expertise required, users, audience, input, output, computer platforms, programming language, strengths, weaknesses, technical contact, and availability.

COMFIE

Hourly simulation of heat transfer through zones. Calculates heating loads and temperatures in each zone.

- Expertise required: High level of computer literacy not required;
- Users: More than 100 users.
- Audience: Architects and mechanical engineers. Energy consultants
- Input: Building geometry, thermal characteristics, internal loads, schedules. Input by the program's user interface.
- Output: Graphs and tables of heat loads.
- Computer platform: PC-compatible.
- Programming language: Pascal.
- Strengths: Can model all of the passive solar strategies.
- Weaknesses: No detailed mechanical system model.
- Contact: IZUBA Energy, www.izuba.fr/logiciel/pleiadescomfie
- Cost: $1,000.

DEROB-LTH

Hourly simulation of building envelope systems. Calculates heating and cooling loads and comfort indices. Detailed treatment of solar gains, window properties, and shading.

- Expertise Required: Knowledge specific to building energy science. Users: More than 150 users.
- Audience: Students, researchers, and consultants.
- Input: Air flows; building geometry, thermal characteristics, internal loads, schedules. Input by the program's user interface.
- Output: Graphs and tables of heat loads; surface diagrams of comfort indices.
- Computer platform: PC-Windows compatible.
- Programming language: FORTRAN, Visual Basic.
- Strengths: Can model all of the passive solar strategies.
- Weaknesses: No detailed mechanical system model.
- Contact: Lund Institute of Technology, www.derob.se.
- Cost: Euro 500 for research, Euro 1,000 for commercial.

DOE-2 (and interfaces: PRC-DOE-2, VisualDOE, Building Design Advisor, eQuest)

DOE-2 was one of the first two whole-building hourly simulation programs. The Simulation Research Group at Lawrence Berkeley National Laboratory (LBNL) maintains the calculation engine, and there are five to seven vendors that offer versions with user-friendly interfaces. Examples are PRC-DOE-2 (paul.reeves@doe2.com) and VisualDOE (www.archenergy.com/products/visualdoe). Building Design Advisor (BDA) is an interface with DOE2.1E that facilitates daylighting, electric lighting energy, and building simulation also produced by LBNL. eQuest is an interface for, and includes, DOE2.2, and it is very popular at schools and among firms that provide energy modeling (www.DOE2.com).

- Expertise Required: High level of computer literacy required; two days of training required minimum. Expertise often obtained through coursework in an engineering degree program.
- Users: More than 1,000 users.
- Audience: Energy consultants; A-E firms; researchers; utility programs; education.
- Input: DOE-2 uses its own syntax, called "Building Description Language," which generally requires a more user friendly interface to populate. BDL describes building geometry and HVAC systems and plants.
- Output: Dozens of standard reports; user can customize reports from energy variables calculated by the program.
- Computer platform: PC-compatible, Sun, DEC-VAX; IBM RS6000, NeXT, UNIX, DOS, VMS.
- Programming language: FORTRAN 77.
- Strengths: Very detailed building description and calculations. Very detailed HVAC models; includes economic models. Wide base of users and user support groups. Can model all of the passive solar strategies.
- Weaknesses: High level of detail makes it time-consuming to get results.
- Contact: Lawrence Berkeley National Laboratory, Mail Stop 90-3147 1 Cyclotron Road, Berkeley, CA 94720; Website: simulationresearch.lbl.gov
- Availability: Available from Energy Science and Technology Software Center (estsc@adonis.osti.gov). Also available from vendors that produce interfaces.
- Current Release: Version 2.1E; version 2.2.
- Cost: $300 to $2,000 depending on vendor and product. For a list of vendors and products see gundog.lbl.gov/dirsoft/d2vendors.html.

Energy Plus (and Interfaces: Design Builder, Autodesk Green Building Studio, ECOTECT, SolarShoeBox)

EnergyPlus combines the capabilities of DOE-2 and BLAST, and is the focus of most development efforts recently. Public funding goes into developing the calculation engine and private companies make user-friendly interfaces for the program.

One of the best such interfaces is Design Builder, which displays three dimensional solid models of wall thicknesses, room areas, and volumes, and allows import of this information from CAD models (www.designbuilder.co.uk). For architects or people that use CAD, Autodesk Green Building Studio facilitates transfer of geometric data to either DOE2.2 or EnergyPlus by means of the interoperability schema gbXML. SolarShoeBox is a program that makes it easy to set up an EnergyPlus model of a rectangular room for passive solar direct gain (www.archiphysics.com). ECOTECT allows evaluation of design alternatives early in conceptual and schematic design phases ([www.autodesk.com/ecotect-analysis]).

- Expertise required: Building energy education required. Standard training is two days regarding EnergyPlus and then one additional day on one of the interfaces.
- Users: More than 85,000 downloads.
- Audience: Energy engineers and consultants, research scientist; educators.
- Input: Extensive detail on building envelope and mechanical systems, utility rate structures, etc. input by interface by private developer or by ASCII input file.
- Output: Dozens of reports on building energy use patterns and summary tables output into graphical outputs in interfaces by private developers or into ASCII output file.
- Computer Platform: XP/Vista, Mac OS, Linux.
- Programming Language: FORTRAN 90 2003.
- Strengths: Very detailed results available. Good validation of results. Weather data for 2,000 sites worldwide. Large community of users and support groups.
- Weaknesses: Takes a lot of time to learn how to use the program and takes a long time to generate results for each project.
- Contact: US Department of Energy. Website: apps1.eere.energy.gov/buildings/energyplus/].
- Current Release: EnergyPlus 7.1.0.
- Cost: Free download at apps1.eere.energy.gov/buildings/energyplus/ also available with interface from private developers. Contact vendors listed at www.energyplus.gov for pricing.

Energy Scheming

Simulates one typical 24 hour day for each of the four seasons.

- Expertise required: Basic energy concepts
- Users: More than 600 users.
- Audience: Students, researchers, and architects.
- Input: Building geometry, climate data, thermal characteristics, internal loads, schedules. Input by the program's user interface.
- Output: Printed report with text and graphs.
- Computer platform: Macintosh SE.
- Programming language: MPW C.
- Strengths: Can model mass and shading for passive solar strategies.
- Weaknesses: No detailed mechanical system model or monthly energy estimates.
- Contact: Energy Studies in Buildings Laboratory; GZBrown@aaa.uoregon.edu.
- Cost: $195 for professionals; $49 for students.

ESP-r

ESP-r is an hourly simulation based on conservation equations. It has its own simulation engine but people also use it to create input files for EnergyPlus. It also has its own utility for entering building geometry but accepts from CAD tools as well.

- Expertise required: Building energy education and special training required.
- Users: More than 100.
- Audience: Mostly researchers, some consultants, educators.
- Input: Extensive detail on building envelope and model details into input facilities or import utilities in the program.
- Output: Output format is rather general and focused on integrating relevant criteria.
- Computer platform: many including PC Windows and Mac.
- Programming language: C and FORTRAN 77 and 90.
- Strengths: Can use short time steps (second, minute, hour). Very detailed analysis. Good validation of software.
- Weaknesses: Not specifically designed for solar analysis; detailed features are hard to figure out.
- Contact: University of Strathclyde. Website: www.esru.strath.ac.uk.
- Cost: Free download at the website.

Hot2 XP and HOT2000

Specifically designed for residential passive solar. Hot2 XP is a simplified version of HOT2000.

- Expertise required: Homebuilding experience; experience with how houses are built and operated.
- Users: More than 300.
- Audience: Builders, consultants.
- Input: Menu-driven input screens. Basic input is simple building geometry and location data. Library of component defaults can be accessed and changed.
- Output: One nontechnical report for homeowner and technical report for designers. Can compare house alternatives side-by-side.
- Computer platform: many including PC Windows 98 or Windows NT.
- Programming language: C++ and FORTRAN.
- Strengths: Useful, timely, and affordable to get results to inform design decisions on buildings.

- Weaknesses: Does not model multizone systems.
- Contact: Natural Resources Canada. Website: http://canmetenergy.nrcan.gc.ca/software-tools/hot2000/84Cost: Free download.

RETScreen

The RETScreen model for passive solar heating is not as developed as it is for the other renewable energy technologies in RETScreen. It consists only of changing window properties from a base case to a more efficient window. It does not address calculations of loads and sizing. The training material that Natural Resources Canada provides along with this software does have a worthwhile description of passive solar and cooling load avoidance.

- Expertise required: None; training material included in software.
- Users: >135,000 worldwide in 222 countries.
- Audience: Engineers, architects, technologists, planners, facility managers, and educators.
- Input: Existing window dimensions, orientations, and properties (SHGC, U-value); replacement window properties.
- Output: Energy savings in heating and cooling from replacing windows. All outputs are in Excel and can be copied, printed, or saved to PDF format.
- Computer platform: Windows 2000, XP, Vista.
- Programming language: Excel, Visual Basic, C#.
- Strengths: Easy and quick comparison of window properties.
- Weaknesses: Not a whole-building model with mass and other passive solar considerations—just a window performance calculator.
- Contact: Natural Resources Canada, CANMET Energy Technology Centre - Varennes, 1615 Lionel-Boulet, P.O. Box 4800, Varennes, Quebec J3X 1S6, Canada; Telephone: 450-652-4621, Fax: 450-652-5177; Email: rets@nrcan.gc.ca; Website: www.retscreen.net/.
- Cost: Free.

Solacalc

Solacalc calculates heating and cooling loads and solar gain in residential buildings. It compares designs with a reference case that does not have solar to estimate savings and economic benefits.

- Expertise required: Spreadsheets and building energy systems.
- Users: More than 30.
- Audience: Architects, engineers, builders.
- Input: Building geometries and material properties.
- Output: Spreadsheet tables and graphs of energy use for heating and cooling.
- Computer platform: PC Windows 95.
- Programming language: Borland Delphi.
- Strengths: Easy, quick, and standardized method, widely accepted in Europe.
- Weaknesses: Monthly calculation not very detailed.
- Contact: Equinland Limited Website: www.solacalc.com/.
- Cost: $39.95 at www.solacalc.com.

SUNREL

SUNREL, an upgrade of SERIRES is designed especially for passive solar heating; models direct gain, sunspace and thermal storage wall and includes features such as advanced glazing and movable shading and insulation.

- Expertise required: Education in heat transfer and thermodynamics.
- Users: >100. Basis of New York state energy audit program.
- Audience: Energy consultants, research scientists, designers.
- Input: Geometric description of building; thermal and optical properties of materials; hourly weather data.
- Output: Temperature and energy flows for any component of the building hourly or integrated weekly, monthly, yearly.
- Computer platform: PC compatible using DOS.
- Programming language: FORTRAN.
- Strengths: Good foundation in thermal network approach.
- Weaknesses; Models only heat transfer in building components; no detailed model for HVAC or other aspects affecting building systems.
- Contact: National Renewable Energy Laboratory,1617 Cole Blvd, Golden, CO 80401; Telephone: 303-275-3000; Website: www.nrel.gov/sunrel/.
- Cost: Free for registered users, see http://www.nrel.gov/buildings/sunrel/. Derivative products offered for a fee.

SOLAR-5 (HEED)

SOLAR-5 is now incorporated into Home Energy Efficient Design (HEED). SOLAR-5 is a detailed hourly simulation with a lot of utilities for handling input and output (to interpret results). Models heat flow in and out of thermal mass. Program allows for early analysis with only four pieces of information: floor area, number of floors, location, and building type; and then user can modify default values as design develops.

- Expertise required: Some expertise with computer systems and building energy science required.
- Users: >1,000.
- Audience: Very popular in education, consultants.
- Input: Geometric description of building; thermal and optical properties of materials; hourly weather data.
- Output: Tables of energy use; 3-D graphs of temperature and energy flows by hour and month.
- Computer platform: PC Windows.
- Programming language: Visual FORTRAN.
- Strengths: Credible hourly simulation; easy to use early in design due to default building types.
- Weaknesses; Mechanical system models lack detail.

- Contact: Department of Architecture and Urban Design, University of California, Los Angeles. Website: www.energy-design-tools.aud.ucla.edu/
- Cost: Free download.

TRNSYS

TRNSYS (Transient System Simulation Program) framework is very effective for mechanical heating systems and works for systems of building components (wall, windows, etc,) as well. Models infiltration and solar heat gain. Lumps thermal capacitance into a node. TRNSYS includes a graphical interface, a simulation engine, and a library of components that range from various building models to renewable technologies. TRNSYS also includes a method for creating new components that do not exist in the standard package.

- Expertise required: Specific knowledge of the TRNSYS software would be necessary to model buildings.
- Users: Over 500.
- Audience: Engineers, consultants, researchers, consulting firms, architects.
- Input: Input files can be ASCII text or can be generated by using a graphical user interface, known as the Simulation Studio. Displays perspective view of building with walls, windows, etc.
- Output: Life-cycle costs; monthly summaries; annual results; histograms; plotting of desired variables (by time unit). It is also possible to plot variables as the simulation progresses.
- Computer platform: Windows 95 or higher (98, NT, 2000, ME etc.) for TRNSYS interface programs (distributed source code will compile and run on any FORTRAN platform).
- Programming language: FORTRAN, C++.
- Strengths: Modular approach and component library. Very detailed models. Extensive documentation. Graphical interface to drag-and-drop components for creating input files (Simulation Studio)
- Weaknesses: Training required for users. Time consuming to generate results per project.
- Contact: Solar Energy Laboratory, University of Wisconsin, 1500 Engineering Drive, Madison, WI 53706 United States; Telephone: 608-263-1589, Fax: 608-262-8464; Email: trnsys@sel.me.wisc.edu; Website: sel.me.wisc.edu/trnsys.
- Cost: Version 16, for commercial use $4,200, educational use is $2,100.

Window 4.1

Calculates window performance parameters such as U-value, SHGC, and visible transmittance. User specifies details of glass and construction of window.

- Expertise required: Basics of window construction and properties.
- Users: Over 2000.
- Audience: Window manufacturers, engineers, consultants, researchers, sales.
- Input: Window construction details entered by users or read from other LBNL tools (FRAME and OPTICS).
- Output: Total window properties U-value and SHGC
- Computer platform: PC Windows.
- Programming language: FORTRAN, C.
- Strengths: Provides standardized calculation of window properties for use in window design and other analysis programs.
- Weaknesses: Not whole-system model—only calculates window properties, not performance under conditions.
- Contact: Lawrence Berkeley National Laboratory; Website: windows.lbl.gov/software/window/window.html.
- Cost: Free download from website.

CODES AND STANDARDS RELATED TO PASSIVE SOLAR HEATING

Standards related to passive solar heating and solar cooling load avoidance are embodied in building codes related to energy and quality. A list of codes and standards related to buildings in the US is on the website www1.eere.energy.gov/buildings/codes.html.

Check with the local jurisdiction to find out what codes apply. The most recent version of a code or standard might not be the one adopted by the jurisdiction. Some of the organizations that promulgate standards and certification of buildings are listed here. This list is not inclusive, rather just a reference of some of those most related to integration of passive solar into a building:

American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE)

ASHRAE (www.ashrae.org) is the leading organization forwarding building energy performance standards in the US. Topics include green building construction, CFC emissions, commissioning, and solar energy. These include:

- ASHRAE 90.1 Energy Standard for Commercial Buildings Except Low-Rise Residential Buildings
- ASHRAE 55 Thermal Environmental Conditions for Human Occupancy prescribes target comfort conditions and allowable temperature swing within a space to store solar thermal heat.
- ASHRAE 62 Ventilation for Acceptable Indoor Air Quality: air flow rates for heating load calculations.
- ASHRAE Passive Solar Heating Analysis
- ASHRAE has also developed a green building standard and design guides for different types of buildings.

International Code Council (ICC)

ICC (www.iccsafe.org or www.intlcode.org) publishes several codes that address passive solar construction.

- IECC International Energy Conservation Code: recommends insulation levels.

- IBC International Building Code (2012): includes requirement that heating system be capable of maintaining 68F in every room without intervention.
- IRC International Residential Code for One- and Two-Family Dwellings (2012).
- IFC International Fire Code (2012).
- IgCC International Green Construction Code (2010).

Unified Facilities Criteria

Unified Facilities Criteria provides specifications for branches of the military:

UFC 3-440-03N Passive Solar Buildings (http://wbdg.org/ccb/DOD/UFC/INACTIVE/ufc_3_440_03n.pdf).

US Green Building Council

The US Green Building Council (www.usgbc.org) accredits professionals and certifies buildings according to a point system where each point is well documented and refereed. There are many products for different types of building projects offered under the general title of:

USGBC Leadership in Energy and Environmental Design (LEED) Green Building Rating System.

OPERATION AND MAINTENANCE OF PASSIVE SOLAR HEATING SYSTEMS

In one view, passive solar heating systems have a lot of operator intervention and maintenance. In another view, a building operator would have to operate window openings and coverings anyway, and would have to maintain the integrity of the materials anyway, so no additional maintenance is required.

Operator Intervention

- Open windows to provide cooling
- Close blinds to reduce solar heat gain
- Close drapes to reduce heat loss at night

Increased Maintenance

- Increased area of glass entails more glass cleaning and more breakage
- Intense solar heat degrades window gaskets and surface finishes
- Remove accumulated dust and dead bugs from rock bin storage and between window and thermal storage wall.

CASE STUDIES OF PASSIVE SOLAR SPACE HEATING SYSTEMS

Here we consider three case studies, one direct gain, one sunspace, and one thermal storage wall.

Passive Solar Direct Gain, NREL Thermal Test Facility, Golden, Colorado

The Thermal Test Facility at NREL is an 11,000 ft^2 multipurpose laboratory facility that enables indoor testing of HVAC components. The long side of the TTF shown in figure 6-14 faces south. The building features optimized window-to-wall ratios, increased insulation, daylighting and controls, passive heating and exposed mass, engineered window shading, and south-facing clerestory windows into the rooms on the north side of the building (NREL 2012). These measures reduce energy consumption by 66 percent compared to a typical building of this size. Direct solar heat gain is admitted into the row of offices on the south side of the building. Occupants often use blinds to block glare and radiant heat. The next row of windows admits light high into a corridor and more workspace. And the third row admits light high into high-bay laboratory space.

Passive Solar Sunspace, NREL Solar Energy Research Facility, Golden, Colorado

The Solar Energy Research Facility (SERF) is a 115,000-square-foot laboratory at the National Renewable Energy Laboratory in Golden, Colorado. The building was completed in 1993 and houses 170 researchers in 42 laboratories. The building cost $19.6 million, or about $170 per square foot for design and construction. The building incorporates energy saving features that make it one of the government's most energy efficient buildings. Annual energy costs are reportedly 36 percent lower than a typical building of this size. The front of the building faces south to capitalize on sunlight for heating and daylighting and features the sunspace shown in figure 6-15. Offices and adjoining

Figure 6-14. Direct-gain passive solar heating at the Thermal Test Facility Building, NREL, Golden, Colorado. (Photo by Warren Gretz, courtesy of DOE/NREL, PIX# 12637)

Figure 6-15. Passive solar heating is provided by a sunspace at the Solar Energy Research Facility Building, NREL, Golden, Colorado. (Photo by Warren Gretz, courtesy of DOE/NREL, PIX# 02194)

Figure 6-16. Thermal storage wall at the NREL Visitor Center, Golden, Colorado, is articulated with direct gain through view east facing windows and west-facing thermal storage wall elements. (Photo by Warren Gretz, courtesy of DOE/NREL, PIX# 12637)

corridors are daylit. Window shades are controlled by photovoltaic sensors. The building also uses selective glass on the west side, where it is desirable to reduce heat gain but maintain high daylight transmission. This sunspace gets a little warm during the day and a little cool at night but contributes to the energy performance of the occupied space behind it (NREL 1998).

Passive Solar Thermal Storage Wall, NREL Visitor Center, Golden, Colorado

Passive solar energy features and other measures help cut energy costs and optimize building performance. The building has an innovative combination of direct gain and thermal storage wall on the south side. As shown in figure 6-16, the wall has five sections, each angled in a "V" shape. Windows facing east within the V open to the space. Thus on a cold morning the space gets the direct gain to heat up. The part of V facing west has the same glazing as the east windows, but backs directly to a thermal storage wall. A small airspace separates the wall from the glass. Direct solar radiation is absorbed by the black paint surface of the wall, trapped by the glass, and conducted into the mass wall to gradually heat the room later in the day. Horizontal beams in front of the windows act as an overhang to prevent direct sunlight from entering during the summer (NREL 2009).

Example

Procurement Specifications for Passive Solar Thermal Storage Wall

Most of the specifications related to the passive solar heating system of a building will already be described in the parts of the specification that address windows and floor materials. The Construction Specification Institute publishes the format for specifications according to division numbers. Some examples of language related to passive in the divisions are:

Insulation shall have 50 percent recycled content and low air emissions.

Low-slope roofs shall have initial solar reflectance of 0.65 or greater and maintain 0.50 or greater three years after installation.

Windows shall carry National Fenestration Rating Council energy performance label. Windows shall have a heat loss coefficient U-value of 0.30 or less.

Temperature control of heating system is coordinated with passive solar storage strategy (lower set point, larger temperature swing).

The following example shows some text from a procurement specification related to the selective surface of the thermal storage wall, which is perhaps the most specialized component; the other components being only insulation, windows, concrete floors and concrete or masonry walls.

Section Trombe Wall Selective Surfaces:

Part 1: General

1.1 Description

A. The work of this section consists of furnishing and installing a selective surface on Trombe walls.

1.2 Related Sections

A. Concrete unit masonry—Section 04201
B. Glazing—Section 08810

1.3 Submittals

A. Product data: Submit manufacturer's product data on material, including published data. Submit manufacturer's installation instructions.
B. Samples: Submit 30 cm (12-inch) square sample of selective surface material.

Part 2: Products

2.1 Materials and Components

A. Selective surface
   1. Copper foil with shiny nickel outer surface overcoat and a thin layer of black chrome oxide with an absorbance greater than 0.95 and an emittance less than 0.11, Solar-L-Foil as available from MTI Solar, Inc., 220 Churchill Avenue, Somerset, NJ; telephone: (732) 246-1000, or approved equal.
   2. Adhesive: As recommended by the Selective Surface manufacturer or G590 or #2227 as available from Beacon Adhesives, Inc., 125 South MacQuesten Pkwy. Mount Vernon, NY 10550; telephone (914) 699-3400), or approved equal.
   3. Trombe wall glass. Glass: 5/32-inch thick, fully tempered, low-iron glass. Solar Energy Transmittance to be 90.7 percent or higher. Solatex or Solite Solar Glass as manufactured by AFG Industries; telephone: (800) 251-0441. The AFG glass comes in different finishes. The selection of the finish is made by the architect. Typically, either a Solatex or a Solite Solar Glass is selected to provide a glass with visible distortion to prevent people from seeing the selective coating. The Solite glass has more pattern than the Solatex glass. Glass is typically installed as part of a store-front glazing system.
   4. Trombe wall masonry. Wall is typically poured masonry (8 inches thick) or 8-inch CMUs. CMUs must be completely filled (all cells grouted) leaving no air-voids. Inside of the wall can be finished using similar masonry product such as concrete, stucco, or plaster. No furring, drywall, etc. can be installed on interior surface. Electrical conduit should not be in the wall. Furniture and other obstructions should not be directly against the interior surface of the wall.

Part 3: Execution

3.1 Preparation

A. Do not begin selective surface work until after Trombe wall construction is complete and wall has cured for a minimum of seven (7) days.
B. Clean Trombe wall of dust, dirt, oil, or any other organic or inorganic contaminants. Vacuum immediate wall areas just prior to applying selective surface.

3.2 Installation

A. Install selective surface to full height of Trombe wall exterior surface using adhesive, tools, and methods as recommended by the surface manufacturer.

3.3 Cleaning

A. Clean Trombe wall area promptly after installation. Provide protection of selective surface until Trombe wall is enclosed. Assure Trombe wall is without damage and deterioration at time of acceptance.
B. Clean Trombe wall interior and exterior glazing

Warranty

Submit specific warranties and guarantees, final certifications, and similar documents to the contracting officer upon substantial completion and prior to final payment. All warranties shall be signed by a principal of the contractor's firm and sealed if a corporation. The entire system including windows and other components shall be warranted for weather tightness for ten (10) years from the installer including parts and labor. Provide window manufacturer's limited warranty.

REFERENCES

ASHRAE. 2010. *Thermal Environmental Conditions for Human Occupancy.* Standard 55. Atlanta, GA: American Society of Heating Refrigerating and Air Conditioning Engineers.

Bergquam, J., and J. Brezner. 2003. *Design and Optimization of Solar Absorption Chillers. Public Interest Energy Research.* Sacramento: California Energy Commission.

Butti, Ken, and John Perlin. 1980. *Golden Thread: 2500 Years of Solar Architecture and Technology.* Palo Alto, CA: Cheshire Books.

Demirbas, M. F. 2006. "Thermal Energy Storage and Phase Change Materials: An Overview." *Energy Sources* 1(85): 85–95.

DOE FEMP. 2004. *Procurement of Architectural and Engineering Services for Sustainable Buildings*. Golden, CO: National Renewable Energy Laboratory.

DOE OBT. 2011. "Tools Directory." Office of Building Technologies. apps1.eere.energy.gov/buildings/tools_directory/ (accessed March 16, 2012).

EERE. 2011. "EnergyPlus." EERE.energy.gov. apps1.eere.energy.gov/buildings/energyplus (accessed April 27, 2012).

Energy Savers. 2009. "Liquid-Based Active Solar Heating." Energy Savers. http://energy.gov/energysaver/articles/active-solar-heating. (accessed April 13, 2013).

Hirsch, J. 2009. "eQUEST." www.doe2.com/equest (accessed April 27, 2012).

Incropera, F., and D. DeWitt. 2005. *Fundamentals of Heat and Mass Transfer* (7th ed.) New York: John Wiley and Sons.

LBNL. 2011. "Windows for High Performance Commercial Buildings." Performance. www.commercialwindows.org/performance.php (accessed June 2, 2012).

Marion, W., and S. Wilcox. 1994. *Solar Radiation Data Manual for Flat Plate and Concentrating Collectors,* Edited by M. A. Dunlap. Golden CO: NREL. http://rredc.nrel.gov/solar/pubs/redbook/ (accessed June 14, 2013).

Minister of Natural Resources Canada. 2012. "RETScreen International." (January 16, 2012). www.retscreen.net (accessed August 19, 2012).

NASA LARC. 2012. *Surface Meteorology and Solar Energy*. http://eosweb.larc.nasa.gov/sse/; https://eosweb.larc.nasa.gov/cgi-bin/sse/global.cgi?email=.

NFRC. 2005. "Fact Sheets." National Fenestration Rating Council. http://c.ymcdn.com/sites/nfrccommunity.site-ym.com/resource/resmgr/fact_sheets/nfrc_label_infographic.pdf (accessed March 2013).

NREL. 1998. NREL's Solar Energy Research Facility. www.nrel.gov/pv/facilities_serf.html. (Updated November 28, 2011; accessed April 13, 2013).

———. 2009. "A Model of Energy-Efficient Design." Visitor Center. www.nrel.gov/visitors_center/eed_model.html (accessed July 1, 2012).

———. 2012. *Maximizing Thermal Efficiency and Optimizing Energy Management.* NREL/FS-5500-53657 (March 2012). Available at www.nrel.gov/docs/fy12osti/53657.pdf.

PCM Products Inc. 2011. Phase Change Materials Thermal Energy Storage http://www.pcmproducts.net/files/design_manual.pdf.

PSIC. 1995. *Passive Solar Design Strategies: Guidelines for Homebuilding*. Washington, DC: PSIC and NREL.

RS Means. 2011a. *Green Building Cost Data*. Norwell, MA: Reed Construction Data.

———. 2011b. *Mechanical Cost Data* (34th ed.). Norwell, MA: RS Means & Co.

———. 2011c. *Green Building: Project Planning and Cost Estimating*. Kingston, MA: RS Means & Co.

Sharp, T. 1994. *Energy Benchmarking in Commercial Office Buildings.* Oak Ridge, TN: Oak Ridge National Laboratory.

Solar Components Corporation. 2010. "2012-2013 Energy Saver's Catalog." www.solar-components.com/2010%20Solar%20Catalog.pdf (accessed April 13, 2013).

Steven Winter Associates, Inc. 1998. *The Passive Solar Design and Construction Handbook*. Edited by M. J. Crosbie, New York: John Wiley and Sons.

Walker, A. 1998. "Natural Ventilation." *Whole Building Design Guide*. www.wbdg.org (accessed May 26, 2012).

———. 2008. "The Fundamentals of Natural Ventilation." *Buildings Magazine,* available at Buildings.com, www.buildings.com/article-details/articleid/6587/title/the-fundamentals-of-natural-ventilation.aspx (accessed April 13, 2013).

Walker, A., D. Renee, S. Bilo, C. Kutscher, D. Barley, J. Burch, et al. 2003. "Advances in Solar Buildings." *Journal of Solar Energy Engineering* 125:236–44.

7

Case Studies of Solar Buildings

CASE STUDY: RESIDENCE IN GOLDEN, COLORADO

This solar house was recently renovated with the addition of a rooftop photovoltaic system, a new solar water heating system, and a second sunspace. Figure 7-1 shows these systems on the south side of the house. Ivan Azerbegi of San Francisco and MN2 Architecture of Bailey Colorado provided architectural services and supervised construction. New windows and a new entry vestibule help reduce heat loss. Superefficient appliances such as horizontal-axis clothes washer; refrigerator with the freezer on the bottom; induction cooktop; and LED lighting reduce the need for electricity to around 300 kWh/month. The house was originally built in 1983 by Sunlite Custom Homes as part of a solar demonstration and tour project. The house was designed by Dennis Butte of Denver. Features of the original house include: triple-pane windows (one double-pane and one single-pane window in the same window opening); 6-inch wall sections; passive solar heat gain into most of the rooms, including the use of clerestory windows; sunspace with 1.3 m (four-foot)-deep rock bin thermal storage; and active solar water heating system. The lot has a perfect solar exposure—the house is dug into the south side of North Table Mountain in Golden. It was built as part of a series of solar house demonstrations and benefited from many lessons learned from the previous houses.

The maximum heating degree days for Golden occur in the month of January, for which the monthly total is HDD = 608 Cdays/month (973 Fdays/month). In January, the monthly average solar on the south-facing vertical windows and thermal storage wall is $I_{c,\mathrm{min},\beta = 90}$ = 4.5 kWh/m^2/day. For the solar water heating system mounted facing south at a tilt equal to the local latitude, the solar resource is maximum in June, with a monthly average of $I_{c,\mathrm{max},\beta = 40}$ = 6.1 kWh/m^2/day and annual average of $I_{c,\mathrm{ave},\beta = 40}$ = 5.5 kWh/m^2/day. The photovoltaics are mounted flush on the roof, and the 4/12 pitch of the roof is close to a tilt of latitude minus 15 degrees, which has a maximum solar resource of $I_{c,\mathrm{max},\beta = 25}$ = 6.6 kWh/m^2/day in June and July and an annual average of $I_{c,\mathrm{ave},\beta = 25}$ = 5.4 kWh/m^2/day (Marion and Wilcox 1994).

Photovoltaics

In 2007, when I bought them, the \$2.29 per watt that I paid for nine Schott Solar ASE-300-DGF photovoltaic modules was a good deal. Now they would be much less expensive. Each is rated for 300 watts so the nameplate-rated power of the PV array is P_{STC} = 2,700 W_{DC}. There is no electrical storage battery. Figure 7-2 shows how the array is wired with all nine PV modules in series, for an open circuit voltage of 586 V and an operating voltage of 455 $\mathrm{V_{DC}}$ under performance test conditions. I often observe voltage around 380 $\mathrm{V_{DC}}$. The short-circuit current of the array is i_{sc} = 6.5 A, and the operating current at maximum power point is i_{mp} = 5.9 Amps. The inverter is a Xantrex GT2.5-NA Grid Tied Solar Inverter. The inverter can accept DC voltages between 195 and 550 V_{DC} and converts the power to 240 $\mathrm{V_{AC}}$ alternating current. The AC wires leaving the inverter pass through an AC disconnect and backfeed two breakers labeled “Line 1” and “Line 2” in the house electrical panel. The inverter must disconnect from the panel and cease to deliver electricity if the power to the house is cut off. The settings according to which the inverter will disconnect and reconnect are

Figure 7-1. Photograph of solar home in Golden, Colorado, with roof-mounted photovoltaics, solar water heating and passive solar features. (Photo by author)

adjustable to accommodate utility policy, with default settings for AC high and low voltage, AC high and low frequency, and reconnect delay (seconds) according to UL1741. The cost of the inverter was $1,706

Figure 7-3 shows how the PV modules cover an entire section of the roof. Double-roman cement roofing tiles were removed, roll roofing put down, and stanchions affixed to blocking between the rafters and flashed into the roofing to shed water. A formed steel beam (Unistrut) was laid down between the stanchions to form the mounting rail and the modules bolted to the rail using standard Unistrut hardware. This rack hardware cost $392. In order to install blocking between the rafters, General Construction Concepts Inc. removed the drywall ceiling, installed blocking between rafters, installed the roof rack, and reinstalled the ceiling at a cost of $5,750.

Jefferson County doesn't allow a homeowner to do their own electrical work, and my friend and master electrician Michael Niemeyer installed the final DC and AC wiring. The building

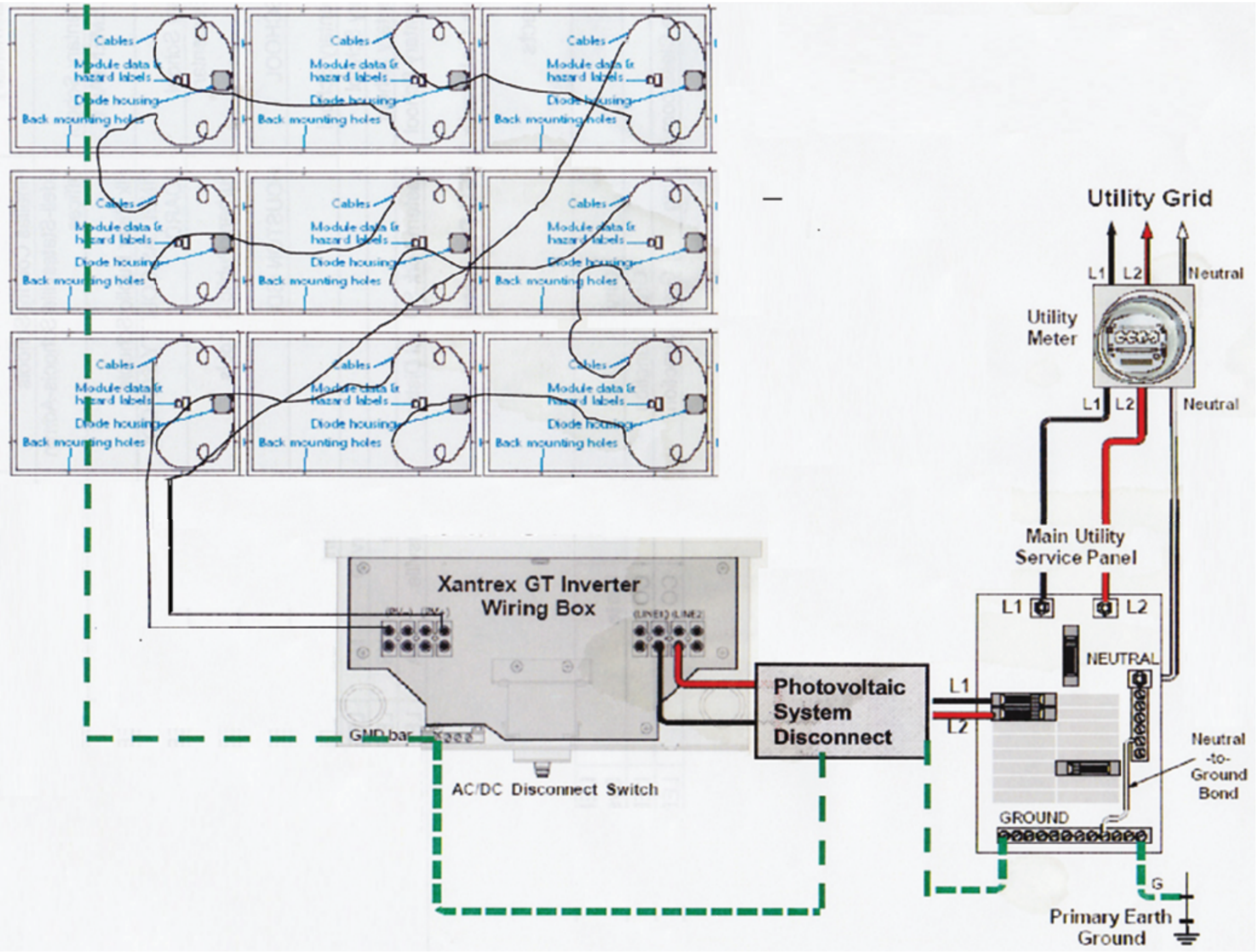


Figure 7-2. Schematic diagram of 2.7 kW_{STC} photovoltaic array at solar home in Golden, Colorado, shows nine PV modules all wired in one series string. (Figure by the author)

Figure 7-3. Photograph of 2.7 kW_{STC} photovoltaic array on solar home in Golden Colorado. (Photo by the author).

inspector didn't recognize the DC disconnect that was supplied with the inverter wiring box, so we added an external one. Figure 7-4 shows these balance of system components installed on an external west wall of the house. I spent $350 on electrical boxes and $1,000 in electrical labor and parts to install the wiring. I spent an additional $500 to add the external DC disconnect.

The total cost of the PV System was $18,397, or $6.81 per watt STC. The Colorado State Constitution requires utilities to get a fraction of their energy from solar, and Xcel Energy satisfies that requirement by purchasing "Renewable Energy Credits" from PV systems owned by utility customers. This system received an $11,000 payment in exchange for ownership of the RECs for 20 years of energy production from the system. The system delivers between 7 and 14 kWh on a clear day depending on the season. At the moment of this writing, at 2:43 pm on July 27 2012, the PV system is producing 2,059 W, and has produced 9.7 kWh so far today. Under cloudy conditions the system still produces a small amount of energy, but when covered by a layer of snow the inverter is off with "low voltage" display message. Annual energy delivery is estimated at 4,097 kWh/year, which exceeds the 3,600 kWh/year anticipated annual electrical energy requirement of the super-efficient home.

Figure 7-4. Photograph of photovoltaic balance of system components. From left to right: DC disconnect; inverter (2.5 kW, 240 VAC); AC disconnect; utility interconnection in building electrical panel; and bi-directional utility meter. (Photo by the author)

Solar Water Heating System

First, water efficiency measures reduce hot water consumption. We replaced the clothes washer with a horizontal-axis one, reducing hot water use by around 40 l (10 gallons) per full load; we replaced a large iron bathtub with a smaller acrylic one and insulated it; and we installed a small pump on a timer that circulates hot water up to the shower in the morning, so that we don't need to waste water and energy waiting for the running water to heat up.

I stopped to talk to Fariborz Mahjouri at the Thermomax booth at a conference in Denver in 2005. He had a solar collector set up on the exhibit-hall floor that he didn't want to ship back to Maryland, and I bought the whole kit, including solar collector, controller, pump, and expansion tank, for $2,500. I bought the water storage tank for $700 but it cost $500 to have it delivered. I probably spent another $1,000 at the hardware store for pipe, valves, and insulation. As shown in Figure 7-5, the system consists of 30 Thermomax Mazdon evacuated tubes that plug into a single manifold at the top. Each of the tubes has a solar absorber area of 0.10 m^2 (1.1 ft^2), for a total absorber area of 3.0 m^2 (33 ft^2). All are supported by a stainless steel frame that is very strong considering its light weight. Due to some space between the tubes, the rack is 2.0 m long by 2.2 m wide for a total area of 4.4 m^2 (48 ft^2). The entire collector weighs 75 kg (165 lbs). Fariborz helped me install it over the weekend. It was

Figure 7-5. Evacuated-tube solar collector for heating domestic hot water at solar home in Golden, Colorado. (Photo by the author)

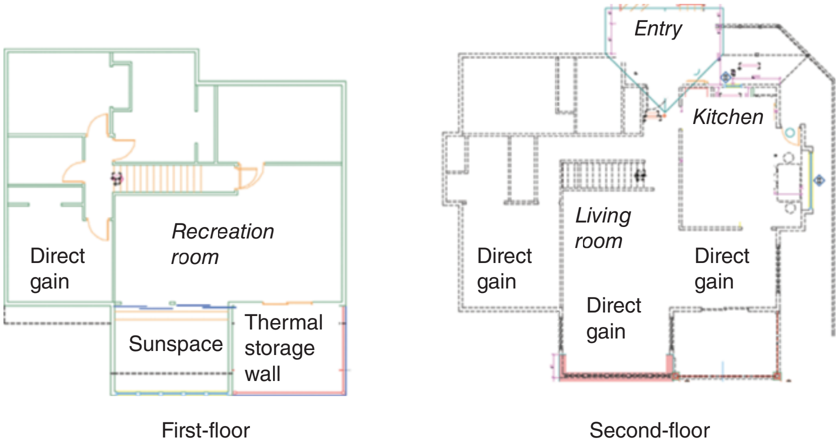


Figure 7-6. Floor plan of solar home in Golden, Colorado. (Figure by the author)

easy to haul the rack parts, header, and tubes up to the roof by hand—conventional flat plate collectors would have required a crane.

The flow rate through the collector of 0.05 l/s (0.8 gallons per minute) results in a pressure drop of 1981 Pa which is maintained by a Grundfos USP 15–58FC pump. The pump is turned on and off by a Thermomax SMT100 controller based on the measured temperature difference between the solar collector manifold outlet and a temperature near the middle of the storage tank. The storage tank is 400 l (105 gallon) volume with two heat-exchanger coils in it manufactured by Steibel Eltron. The lower heat exchanger coil receives heat from the solar collector loop, and an upper heat exchanger coil received heat from a natural-gas fired boiler. Thus the solar can heat the whole tank and is controlled based on the temperature measured in the middle of the tank, and the fossil fuel can heat the top of the tank controlled by temperature measured at the top of the tank.

The efficiency curve from the standard performance test for this particular collector is reported as values $F_R\tau\alpha = 0.542$ and a $F_RU_L = 1.71$ W/m^2/C (0.3 Btu/hr/ft^2/F). In terms of annual performance the system is expected to deliver 10.2 kWh/day (34.8 Btu/day) (SRCC 2012). Note that although this system is much smaller and less expensive than the PV system, the expected delivery of 10 kWh/day is about the same for the two systems. Of course, such a direct comparison is unfair since one delivers electricity and the other one delivers heat. The system is capable of delivering almost all of our hot water, and the storage tank is often piping hot. After a stretch of cloudy days, the water at the tap begins to feel cold and I have to manually enable the natural-gas fired heater to heat the tank.

Direct-Gain Passive Solar Heating

The architectural program is not compromised to accommodate the solar features. The compact floor plate is almost square. In each of the four corners are: living room; dining room; kitchen; and access to bedrooms and bathrooms. Most of the rooms have direct solar heat gain in winter through south-facing windows. There are south-facing clerestory windows at the ridgeline of the roof to let sunlight into the north side of the house. Along the north wall are located closets, pantries, and the entry vestibule- unoccupied spaces to reduce the effect of heat loss through the north wall. On the south side are two sunspaces on the first floor and direct gain windows on the second floor. The most frequently occupied spaces—kitchen, recreation room, master bathroom—are neither on the north side nor the south side but in-between. The floor plan is shown in Figure 7-6.

Sunspace Passive Solar Heating

The sunspaces are very hot during the day, although they are very pleasant places to be for many hours of the year. Heat flow from the overheated sunspaces to the rest of the house is controlled by opening and closing double-pane sliding glass doors. The sunspace original to the 1983 construction has a very clever heat storage arrangement shown in the schematic diagram of Figure 7-7. The sun coming through the large windows heats the floor. Air is drawn in through the spaces between the 3 5/8 inch (7 cm) floorboards and down through a four-foot deep bin of rounded rocks. The rocks are nominally 1 or 2 inches (2 to 4 cm) in diameter. Air from the plenum underneath the rock bin is evacuated by the fan and discharged back into the

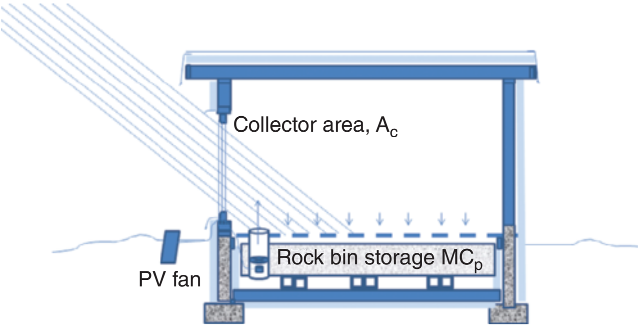


Figure 7-7. Schematic diagram of sunspace with rock-bin thermal storage at solar home in Golden, Colorado showing fan-forced storage of solar heat in rock bin. (Figure by the author)

Figure 7-8. Sunspace with rock-bin storage under transpired floor at solar home in Golden, Colorado. Air duct into rock bin is visible in center of the south side of the room. (Photo by the author)

room. When the sun sets, the PV powered fan stops, and heat rises from the rock by natural convection. This is a very effective coupling of mass to the solar resource. The spacing between the floorboards and the PV-powered fan are visible in Figure 7-8.

Thermal Storage Wall (Phase Change Material)

A new room was added in 2007 with a thermal storage wall arrangement. Six Enerphase phase change thermal storage panels by Dow are mounted in the inside of window openings on the lower portion of the south wall as shown in Figure 7-9. Each 10-kg (22-lb) panel stores 2500 kJ (2,332 Btu) as latent heat at a transition temperature of 32 C (94 F). There are view windows above the 28-inch sill height which admit direct solar heat gain onto the 6-inch-thick (15 cm) concrete floor. Figure 7-10 is an infrared image of two of the phase-change panels in a transition between liquid and solid state.

Figure 7-9. Phase change panels in thermal storage wall at solar home in Golden, Colorado. (Photo by the author)

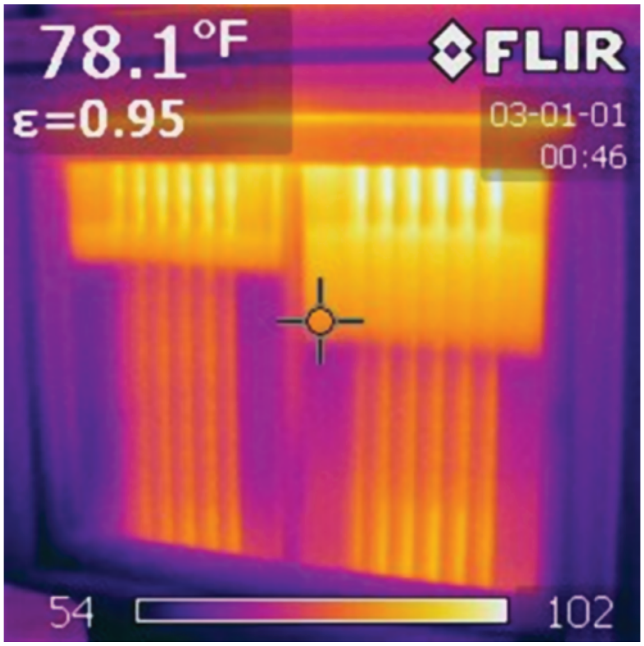


Figure 7-10. Infrared image of phase change panels undergoing transition in thermal storage wall at solar home in Golden, Colorado. (Image by the author)

CASE STUDY: RED ROCK CANYON VISITOR CENTER, LAS VEGAS, NEVADA

Educating the many people that move to Las Vegas about living in the delicate Mojave Desert is a priority for the Bureau of Land Management (BLM), the Red Rock Canyon Interpretive Association, the Friends of Red Rock Canyon, and the Master Gardeners. Architect Les Wallach FAIA and the professionals at Line and Space LLC, John Birkinbine, Henry Tom, and Bob Clements, applied this priority to the design of a new visitor center to house these programs at Red Rock Canyon National Conservation Area, just west of Las Vegas in Nevada. The exhibit designer was Gerald Hilferty and Associates. In 2005, Pat Fleming of the Department of the Interior National Science and Technology Center asked Arun Jhaveri of the DOE Federal Energy Management Program for help with the solar aspects of the design, and NREL was assigned to provide the assistance. Straub Construction won the $17.1 million contract to construct the complex. The project included an 808-m^2 (8,700 ft^2) arrival building and 4,089 m^2 (44,000 ft^2) of outdoor exhibit space. The project also involved renovating an 743 m^3 (8,000 ft^2) administration building and a new 102-m^2 (1,100 ft^2) visitor contact station.

Figure 7-11. A palette of natural materials and a low profile help the Red Rock Canyon Visitor Center merge with the landscape. (Photo by Robert Reck, courtesy of Line and Space LLC)

Helix Electric Inc. installed the photovoltaic and building electrical systems. The building was dedicated on April 10, 2010 and is shown in Figure 7-11.

The facility provides an outdoor experience which will instill in about 1 million visitors a year a sense of personal responsibility for the land's well-being and introduce them to the geology, science, art, and culture of nearby Red Rock Canyon. The building exemplifies how to exist in the desert by extending the usability of outdoor space, providing ample shade, harvesting rainwater, generating its own energy, and using natural and durable materials. The hope is that visitors will realize the benefits that these systems can offer, and then apply some of the same concepts in their own decisions. The project has received LEED Gold certification from the US Green Building Council.

The designers at Line and Space call it the "inside-out" visitor center. Many of the interpretive displays are not in the air-conditioned building, but rather in exterior microclimates, which are kept comfortable through the use of shade, evaporative cooling, and a large energy-efficient fan. The outdoor exhibits occupy around 4089 m^2 (44,000 ft^2) of outdoor exhibit space, including a desert tortoise exhibit that is home to Mojave Max and eight female tortoises. This shifting of exhibits from air-conditioned interior space to fully day-lit tempered outdoor microclimates leads to significant energy savings for the building owner and access to the desert resource for visitors. The layout of the outdoor exhibits is shown in Figure 7-12. High-efficiency mechanical systems are utilized. Passive solar strategies are used to admit solar heat when needed and to keep solar heat out in summer. Fluid circulated for space heating may be heated by solar collectors or by a 33kW electric water heater. Solar water heating, a transpired solar collector system and a photovoltaic array convert the region's intense sun into useful energy.

Passive Solar Heating and Cooling Load Avoidance

The architectural theme is that of a "big hat" (a roof with ample overhangs). The overhangs create a thermal transition zone where eyes and skin can adjust while moving between the hot, bright, exterior and the cool, shaded interior. The overhangs shade floor-to-ceiling glass in the summer while allowing the low winter sun to enter and warm the space, reducing demand on the building's mechanical system. Figure 7-13 shows a view of the interior of the exhibit space.

Photovoltaics

A ground mounted photovoltaic array is oriented at a south-facing tilt of 36 degrees on pole mounts set in concrete caissons as shown in Figure 7-14. Carefully sited between two earthen berms, the array is hidden from view, and thus not obstructing the view of the surrounding mountains of Red Rock Canyon. The system consists of 360 DG180GX-LD multicrystalline photovoltaic modules manufactured by Kyocera. Each of the modules is 0.99m (39in) wide and 1.341 m (52.8 in) long and is rated for P_{STC} = 180 watts under STC conditions. The rated power of the entire array

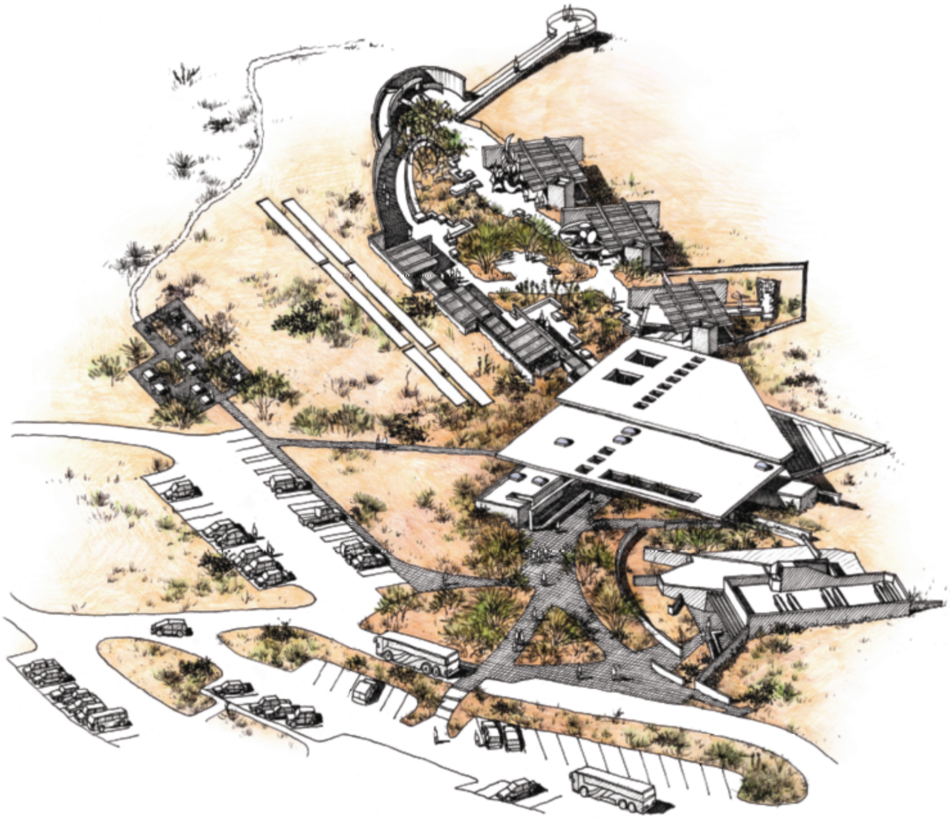


Figure 7-12. Layout of the Red Rock Canyon Visitor Center facility from an aerial perspective. Much of the program space is located outside of the envelope of the conditioned building. (Image by Line and Space, LLC)

Figure 7-13. This 80-foot-long window provides a dramatic connection to the outdoors. By using a triangular floor plan, the view was maximized with half the floor area of a rectangular plan. (Photo by Robert Reck, courtesy Line and Space LLC)

is 64.8 kW at STC. Under more realistic PTC conditions, the rated power is P_{PTC} = 127 watts per module, and considering the inefficiency in the balance of system, P_{solar} = 35 kW would be a typical power delivery. The total area of the array is A_c = 478 m^2 (5,142 ft^2).

The open circuit voltage of each module is v_{oc} = 29.5 V and the voltage temperature coefficient is 0.106 V/C. The short circuit current is i_{sc} = 8.35 amps. The PV modules are wired together with #10AWG USE-2 wire into combiner boxes with fuses for the positive wires and busbars for the negative and ground wires. Larger dimensional wire from the combiner boxes goes into a DC disconnect and then into a Fronius IG5100 inverter with $240V_{AC}$ output.

The photovoltaic array also provides an interpretive opportunity for visitors. After viewing the array, a computer located in the Visitor Center allows users to see how much energy the photovoltaics are producing and the effects that weather (such as cloud cover) have on its efficiency. Data collected by the

Figure 7-14. Harvesting energy from the sun, the 65-kW_{STC} photovoltaic array provides power to the new Red Rock Canyon Visitor Center, and an interpretive opportunity for visitors. (Photo by Robert Reck, courtesy Line and Space LLC)

Fronius datalogger includes insolation in the plane of the array I_c (W/m^2); ambient temperature $T_{ambient}$ (C); PV module temperature T_{cell} (C); instantaneous power delivery P_{solar} (W); daily energy delivery $E_{solar,day}$ (kWh/day); and annual energy delivery $E_{solar,year}$ (kWh/year).

Active Solar Water Heating and Space Heating

A solar water heater also uses energy from the sun to preheat hot water for staff showers and sinks within the adjacent Administration Building and also to provide heat for the hydronic heating system when available. The system utilizes 2 collectors with 30 evacuated tubes each. The collectors are Vitosol 300-T by Viessmann. They are mounted at a 55 degree tilt on the south side of a rainwater catchment tank as shown in the photograph of Figure 7-15. Each collector frame is 2.126 m (83 in) long and 2.0 m (78 in) wide for a total collector area of A_c = 8.48 m^2 (91.2 ft^2). Considering the space between the tubes, the active absorbing area is around 6 m^2 (66 ft^2). The efficiency curve from the standard performance test for this particular collector is reported as values $F_R\tau\alpha = 0.509$ and a $F_RU_L = 1.09$ $W/m^2/C$ (0.19 $Btu/hr/ft^2/F$). In terms of heat delivery, each collector is expected to deliver 11.5 kWh/day (39.3 Btu/day) on a clear day (SRCC, 2012).

There are two storage tanks in the hot water system. One 80-gallon tank serves sinks and showers in restrooms and a sink in the janitor closet in the Administration Building and has two coils in it, the lower one heated by solar and the upper one heated as a zone off the space heating system. A second 120-gallon tank serves the mechanical heating system for both the Visitor Center and Administration Building, and may also be heated by the solar heating system. The priority is to serve the domestic hot water load, and when that tank is not calling for heat, deliver solar heat to the space heating system.

The solar water heating system is expected to deliver $E_{solar,year}$ = 6,500 kWh (22.1 million Btu/year). Of this, 5,334 kWh (18.2 million Btu/year) goes to the service hot water and 1,166 kWh/year (3.9 kBtu/year goes to the space heating

Figure 7-15. Two solar water heating evacuated tube solar collectors are mounted on a 15,000-gallon tank for harvested rainwater storage. (Photo by Henry Tom, AIA, NCARB, courtesy Line and Space LLC)

load. Solar thermal meets about 96 percent of the water heating load and 6 percent of the space heating load, or 27 percent of the total heat requirement.

Solar Ventilation Air Preheating

Situated along the entry plaza as shown in Figure 7-16, the transpired solar collector is ideally suited for sunny locations with long heating seasons. This metal wall converts as much as 80 percent of available solar radiation to heat using minimal energy. As outside air is drawn through the collector's perforated metal skin by a ventilation fan, its temperature increases by as much as 20 C (40°F). The heated air flows to the top of the wall where it is distributed through ductwork to the restroom interiors. The transpired solar collector provides heating for the restrooms, obviating the need for heating from the mechanical system in these spaces.

The metal wall forming the transpired solar collector faces southeast and returns around the exterior corners of the Visitor Center restrooms, so there is some southwest and northeast exposure as well. The southeast face is approximately 7.3 m (24 ft) wide and 3.3 m (11 ft) high for $A_c = 24.5\text{m}^2$ (264 ft^2) and the returns at the corners are 1.5 m (5 ft) wide and also 3.3 m (11 ft) high which adds 5 m^2 (55 ft^2) facing in each of the southwest and northeast directions. In order to achieve the desired architectural aesthetic, the transpired solar collector was custom fabricated in panels with holes of diameter $d = 1.5$ mm (1/16 in) and spaced apart by the pitch $p = 2.8$ cm (1 1/8 inch). The absorptivity of the oxidized iron surface is around $\alpha = 0.81$, while its emissivity is lower at $\varepsilon = 0.69$, so the rust finish makes an acceptable solar collector surface (Gubareff, Janssen, and Torborg 1960). Figure 7-17 is a close-up photograph showing the appearance of the material and the size and spacing of holes.

Figure 7-16. The transpired solar collection wall captures as much as 80 percent of available solar radiation to heat ventilation air for the restrooms. (Photo by Robert Reck, courtesy of Line and Space LLC)

Figure 7-17. Close-up shows hole diameter and spacing of custom-fabricated transpired solar collector for ventilation air preheating. (Photo by Robert Reck, courtesy Line and Space LLC)

CASE STUDY: RESEARCH SUPPORT FACILITY (RSF) OFFICE BUILDING, GOLDEN, COLORADO

An innovative procurement and building delivery process resulted in one of the most efficient buildings in the world, designed to achieve net-zero energy use and a LEED Platinum rating from the US Green Building Council. The 220,000 ft^2 (20,446 m^2) Research Support Facility (RSF1) building houses 824 employees of the US Department of Energy's National Renewable Energy Laboratory (NREL) in Golden, Colorado. We moved into the RSF1 on August 6, 2010. Subsequently a 137,000 ft^2 RSF2 to house 543 occupants was added in 2011, and covered parking in front of RSF1 and a separate staff parking garage have been added in 2012. The buildings were designed by RNL with engineering by Stantec, and constructed by Haselden Construction. Figure 7-18 is a view of parts of RSF1 and RSF2.

Total construction cost for both RSF1 and RSF2 is reported at \$91.4 million, or \$254/ft^2. The on-site photovoltaics added \$34/ft^2 (dollars per square foot of building floor area) for a total cost of 293/ft^2. The range of building cost in this area span \$100 to \$400 per ft^2, with \$335 cited as the per square foot cost for buildings designed to achieve LEED ratings, so this is just a medium price to pay for the high-performance building—it was not more expensive than many conventional buildings (NREL 2011).

A performance-based design-build process was used to construct the RSF. Preparation of the procurement documents with very clear energy-use metrics were required with specific ways in which performance of the design would be evaluated. The request-for-proposals was issued with three categories of performance: Mission Critical, Highly Desirable, and If Possible. The contract allowed an energy use budget of 10 kWh/m^2/year (34.4 kBtu/ft^2/year) based on the results of modeling what should be possible. This energy use includes a high-performance data center which is responsible for a large part of building

Figure 7-18. The south and east sides of the Research Support Facility at the Department of Energy's National Renewable Energy Laboratory. (Photo by the author)

energy consumption. For the parking garage, the energy use intensity was specified at only 0.2 kWh/m^2/year (0.7 kBtu/ft ft^2/year) (Torcellini et al. 2010). This is 50 percent better than ASHRAE 90.1 Energy Code, and in contrast a typical existing commercial building may use on the order of 30 kWh/ m^2/year (100 kBtu/ ft^2/year). The RSF1 is expected to use 2.3 million kWh/year; RSF2 is expected to use 1.0 million kWh/year, and the parking structures are expected to use 100,000 kWh/year. So the total energy consumption of all the buildings is expected to be 3.4 million kWh/year. In order to achieve net-zero energy, the on-site solar energy systems would have to offset that amount.

Passive Solar Heating and Cooling Load Avoidance

Building orientation and geometry minimize solar heat gain in summer, while admitting just the right amount of solar heat gain in winter. The building is stretched out 780 feet from east to west with the north-south floor plate having a depth of 60 feet. The long narrow floor plate allows for daylight and natural ventilation across the space. Small facades facing east and west minimize heat gain on summer mornings and afternoons. There are three large office bars: the one on the south is three storeys, the one in the middle four storeys, and the one on the north side is five storeys tall. The building is well insulated, with continuous foam-board insulation (R-14) cast inside the precase concrete wall elements. The wall elements have three inches of concrete exterior to the insulation and six inches interior to the insulation, so they add considerable mass. The prefabricated wall elements were delivered with the windows already installed. The roof is also concrete insulated to 5.8 m^{2}C/W (R-33 ft^{2}Fhr/Btu). The view windows are triple pane with a glazing U-value of 0.17 W/m^{2}C (1 Btu/ft^2/F) to minimize heat loss, although the aluminum frames have later been found to be a source of excessive heat loss, despite the thermal break in their construction and the rated U-value of 0.34 W/m^2/C.

In a commercial building such as the RSF, with internal heat gain from busy lights and computers, passive solar design is as much about keeping solar heat out as it is about letting it in. On the south side of the building, there are view windows which admit direct solar heat and light, but there is a corridor along that wall, so the direct sunlight does not strike a work place. Each of these windows is fitted with an external overhang to block the high summer sun as shown in Figure 7-19.

Figure 7-19. Windows on the south side of the RSF buildings. View windows are shaded by surrounds but admit some direct solar heat in winter. Above the view windows are daylight windows, which have no shade but block direct solar heat gain with louvers that reflect daylight toward the ceiling deep in the space. (Photo by the author)

Daylighting

Above the view windows are windows (see Figure 7-19) with a daylighting purpose. They are fitted with reflective louvers that direct the sunlight deep into the space and toward the ceiling. The effect of this redirected uplighting is visible in the interior photograph of Figure 7-20. The daylighting windows are double pane with a U-value of 0.27 for the glazing and 0.44 for the window with frame and a visible transmittance of $\tau_{\text{visible}} = 0.65$. They are selective glass with a lower solar heat gain coefficient of SHGC = 0.38.

The north side also has large windows to contribute quality daylight from the north. The 18 m (60-ft) floor plate is greater than the 13 m (45 ft) recommended by Frank Lloyd Wright, but the ceilings are higher than those of Mr. Wright and white reflective surfaces and the specular reflectors on the daylighting windows transmit the daylight adequately into the center of the floor plate. The window-to-wall area ratio on the south side is 28 percent and on the north side 26 percent.

Automatic lighting controls dim the fluorescent lighting in response to the measured lighting level. Lighting may also be controlled manually by wall switches or by a time clock.

Photovoltaics

Grid-tied photovoltaic systems are included in the design to offset the annual energy use of the facility. All three parts of the building were built with expansive roof tilted 10 degrees from the horizontal and facing south. PV may cover the entire roof area because the roof is kept clear of mechanical and communications equipment. The source of chilled water for air conditioning and heated water for space heating is a central plant in another building. This tilt angle maximizes electricity delivery in the summer. The utility, Xcel Energy, has a net-metering policy that allows excess generation at sunny times to be credit at full retail value for energy used at nonsunny times. The policy allows for generation in excess of the load to be used up to 12 months later.

The PV systems contributing power to the RSF facility include:

- A system rated at $P_{STC} = 450\ \text{kW}_{STC}$ is installed on the RSF1 roof as shown in Figure 7-21. The system is expected to deliver 606,150 kWh/year.
- A system rated at $P_{STC} = 466\ \text{kW}_{STC}$ is installed on the RSF2 roof and is expected to deliver 629,100 kWh/year
- A system rated at $P_{STC} = 1{,}098\ \text{kW}_{STC}$ is installed on the parking garage and is expected to deliver 1,482,300 kWh/year.
- A system rated at $P_{STC} = 524\ \text{kW}_{STC}$ is installed on the covered parking in front of the building and is expected to deliver 707,400 kWh/year.

The total annual energy delivery of all the systems is estimated at 3.4 million kWh/year—enough to rather precisely offset the calculated energy consumption of the RSF buildings. The 450 kW system on RSF1 was financed under a power purchase agreement (PPA) with Sun Edison Inc., in an arrangement that leverages tax credits, tax depreciation, and sale of renewable energy credits (RECs), so that NREL just pays for the power delivered at a favorable rate over the 20-year term of the PPA.

Solar Ventilation Air Preheating

The south-facing vertical wall of three of the office bar wings are clad with transpired solar collector for ventilation air preheating.

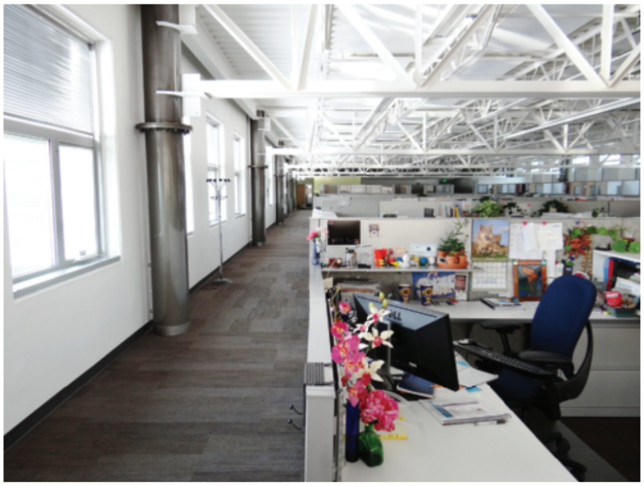


Figure 7-20. Interior offices in RSF1. Direct solar heat gain from the view windows may impinge on the walkway in winter, but not on the work spaces. Daylight through the daylighting windows above the view windows is directed toward the ceiling and deeper into the space by reflective louvers. (Photo by the author)

Figure 7-21. NREL principal engineer Otto Van Geet inspects photovoltaic modules attached to standing-seam metal roof at NREL RSF 2 Building. The clamps used to attach the module frames to the roof are UL-listed for the purpose. (Photo courtesy of National Renewable Energy Laboratory Pix directory)

Figure 7-22. Transpired solar collector is affixed to south wall of RSF to preheat ventilation air. Visible at the bottom of the wall are the ducts that draw the preheated ventilation air into thermal storage within the concrete foundation of the building. (Photo by the author)

One of the systems is $A_c = 144\ \text{m}^2$ (1,560 ft^2); another is $A_c = 398\ \text{m}^2$ (4,290 ft^2); and a third is $A_c = 145\ \text{m}^2$ (1,565 ft^2). Figure 7-22 is a view of the larger of these systems. The perforated metal siding is fastened to a rack which is in turn fastened to the pre-cast wall elements forming the plenum behind the collector. There are a lot of windows on the south side, the perimeter of each of which needs to be flashed and sealed, and in some places nonperforated metal sheet was placed behind the collector to direct uniform airflow through the collector. Air from the transpired collector is drawn down to the bottom of the plenum and into passages within the concrete foundation to provide some thermal storage. Warm air from the office areas or from the data center can also be routed into this thermal storage for use at night. Ventilation air can be drawn in directly or either way through the thermal storage to preheat or precool the ventilation air as directed by the building control system.

Occupant Awareness

Cooperation of the occupants is necessary to achieve net-zero energy use in the RSF. Occupants have control over personal computer and plug loads, and also have the ability to open windows in the RSF. Signals to occupants regarding permission to open windows are delivered by the building computer information system to each personal computer. In each of the building's entry lobbies, there is a display of the energy consumption and status of each building system: lighting, cooling, heating, plug loads, water use, data center use as shown in Figure 7-23. The display reports how much energy the building has consumed next to how much the PV has produced, allowing a direct evaluation of progress toward net zero energy use.

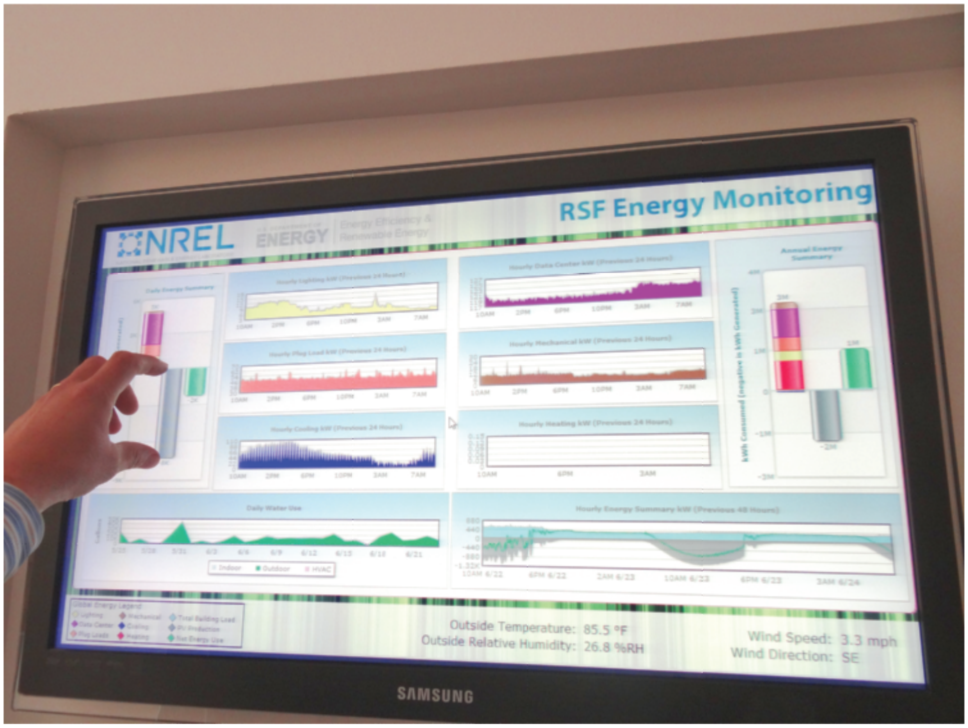


Figure 7-23. Computer data acquisition system computer display in the lobby of the RSF, educating occupants about current energy use and trends. (Photo by the author)

REFERENCES

Gubareff, G. G., J. E. Janssen, and K.H. Torborg 1960. *Thermal Radiation Properties Survey*. 2nd ed. Minneapolis, MN: Honeywell Research Center.

Marion, W., and S. Wilcox. 1994. *Solar Radiation Data Manual for Flat Plate and Concentrating Collectors*. Edited by M. A. Dunlap. Golden, CO: National Renewable Energy Laboratory.

NREL. 2011. *Research Support Facility Leadership in Building Performance*. Golden, CO: National Renewable Energy Laboratory.

Torcellini, P., S. Pless, C. Lobato, and T. Hootman, T. 2010. “Main Street Net Zero Energy Buildings: The Zero Energy Method in Concept and Practice.” 4th International Conference on Energy Sustainability, 2010. Phoenix, AZ: American Society of Mechanical Engineers.

APPENDIX A: NOMENCLATURE

A_c (m^2)	Total surface area of solar cell, module, or array for conversion of solar energy
Bi	Biot number; ratio of external convection to internal conduction
c (m/s)	Speed of light; 3x10^8 m/s
CF	Capacity factor; energy produced (kWh) in a time period divided by rated capacity (kW) and duration of the time period (hours)
C_p (kWh/K)	Specific heat
C_{initial} (\$)	Initial investment cost
$C_{\text{O\&M}}$ (\$/year)	Annual operating and maintenance cost
c_{retail} (\$/kWh)	Price at which energy is purchased from the utility
C_{savings} (\$/year)	Annual energy cost savings
$c_{\text{wholesale}}$ (\$/kWh)	Rate that the utility pays for excess solar energy
d (percent/year)	Discount rate at which future costs are discounted to present value
d (cm)	Pipe diameter
$E_{\text{from utility}}$ (kWh)	Energy to the load from utility over an integration time period
E_{load} (kWh)	Energy required of a load that a solar system serves, integrated over a time period (often 1 day)
$E_{\text{to utility}}$ (kWh)	Energy delivered back onto utility system over an integration time period
E_{saved} (kWh)	Conventional energy saved over an integration period, usually one day or one year
e_{hx}	Heat exchanger effectiveness; actual heat transfer rate divided by ideal rate
F	Fin efficiency factor
F_R	Heat removal factor; ratio of heat delivery calculated at collector temperature to that calculated at fluid inlet temperature.
h (W/m^2/C)	Heat transfer coefficient
i (percent/year)	Inflation rate at which costs escalate from year to year
i (amps)	Electric current
I_c (kW/m^2)	Incident solar insolation; total solar power per unit area in the plane of the array
$I_{c,\text{beam}}$ (kW/m^2)	Beam insolation; power per unit area directly from the sun
$I_{c,\text{diffuse}}$ (kW/m^2)	Diffuse insolation; power per unit area of sunlight scattered by the atmosphere
$I_{c,\text{ground reflected}}$ (kW/m^2)	Ground-reflected insolation; power per unit area of sunlight reflected back toward the solar collector from the ground
i_{mp} (amps)	Maximum power current; current at which power output of PV cell is maximized.
i_{sc} (amps)	Short circuit current
J (Amps/cm^2)	Electric current flux; current through solar cell per unit cross-sectional area
J_{light} (Amps/cm^2)	Current flux of both electrons and holes generated by the incident light
J_o (Amps/cm^2)	Shockley diode reverse saturation current flux
K	Incident angle modifier; ratio of actual transmissivity to calculated transmissivity

k (eV/K).	Boltzmann's constant, a physical constant that relates energy level to temperature (8.617 × 10-5 eV/K)
k (W/m/K)	Thermal conductivity
LCC	Life cycle cost; net present worth of all costs over N years
LCOE	Levelized cost of energy; net present value per kWh produced
$M_{storage}$ (kg)	Mass of thermal storage
N (years)	Analysis period; number of years in the life cycle cost analysis
N_C (1/cm^3)	Density of conduction band states
N_V (1/cm^3)	Density of valence band states
NTU	Number of transfer units; heat transfer coefficient per unit flow rate
Nu_d	Nusselt number; ratio of convection to conduction
P (degrees)	Profile angle; projection of the shading angle of the sun onto the due-south plane
P_{load} (kW)	Instantaneous power consumption of load to be served
$P_{load,\ max}$ (kW)	The most power that a system must deliver (kW) based on the sum of the power of each device being powered simultaneously
P_{motor} (kW)	Power requirement of motor for pump or fan
P_{mp} (W or kW)	Maximum power; maximum output of a PV cell at optimal combination of current and voltage
$P_{rated\ (kW)}$	Rated power output of solar energy system under specified rating conditions
P_{solar} (kW)	Instantaneous power output of solar energy system
PWF	Present worth factor, net present value of $1/year for N years
q (coulombs)	Electrical charge of a single electron (1.602×10^{19} Coulombs)
q_{actual} (W)	Actual heat transfer rate
q_{loss} (W)	Rate of heat loss from a solar collector
q_{useful} (W)	Useful heat delivery from a solar collector; optical gains minus thermal losses
$Q_{FuelSavings}$	Fuel energy savings integrated over time, usually per year
Q_{pump} (kWh)	Energy consumption of the pump integrated over time, usually per year
Q_{solar} (kWh)	Solar energy delivered over a time period, usually one year
Q_{stored} (kWh)	Energy imparted to storage, such as in a thermal storage tank, over a time period
R_{series} (ohms)	Solar cell resistance in series with the load
R_{shunt}(ohms)	Solar cell resistance in parallel with the load
R-value (m^{2}C/W)	Resistance to heat transfer; inverse of U_l
SF	Solar fraction; fraction of load met by solar
SHGC	Solar heat gain coefficient; room heat gain through a window divided by incident solar radiation
SIR	Savings-to-investment ratio, life cycle savings per dollar invested.
SPB (years)	Simple payback period; initial cost divided by annual cost savings
sunhours (hours/day)	Number of hours of full sun per day; incident solar energy (kWh/m^2/day) divided by 1 kW/m^2
T (C,K)	Temperature
t (hrs)	Time elapsed, usually in hours
T (hrs)	Duration of integration period, usually in hours
$T_{ambient}$ (C)	Ambient temperature; temperature of surrounding air
T_c (C)	Temperature of solar collector; ambient temperature plus measured heat loss divided by specified heat loss coefficient
T_{cell} (C)	PV cell temperature
$T_{fluid,in}$ (C)	Temperature of fluid entering solar collector

$T_{\text{fluid,out}}$ (C)	Temperature of fluid exiting solar collector
T_{plenum} (C)	Temperature of air having passed through a transired solar collector into the plenum behind
$T_{\text{stagnation}}$ (C)	Stagnation temperature; temperature which the solar collector will achieve with no fluid flow through it
U_l (W/m^{2}C)	Heat loss coefficient; heat loss per unit area per unit elevation of temperature above ambient temperature
v (volts)	Electric voltage
v_{mp} (volts)	Maximum power voltage; voltage that maximizes power output of a PV cell
v_{oc} (volts)	Open cicuit voltage
V_{face} (m/s)	Face velocity; volume flow rate divided by collector area

Greek Letters

α	Absorptivity; fraction of sunlight not reflected or transmitted, but captured by the surface
α (degrees)	Solar altitude; angular elevation of the sun above the horizon
α_{mp}	Coefficient relating PV cell maximum-power voltage to temperature
α_{sc}	Coefficient relating PV cell short-circuit current to temperature
β_{mp}	Coefficient relating PV cell maximum-power voltage to temperature
β_{oc}	Coefficient relating PV cell open circuit voltage to temperature
γ (degrees)	Solar azimuth; angular displacement of the sun from due south in horizontal plane
δ (degrees)	Declination angle of the earth's axis to that of the sun
δ_{mp}	Coefficient relating PV cell maximum power output to temperature
Δn_{light}(1/cm^3)	Increase in the concentration of electrons induced by exposure to light
ΔP (Pa)	Pressure drop; difference in pressure
ε	Emissivity
ε (eV)	Energy of a photon or an electron, usually in units of eV
ε_{gap} (eV)	Energy required to raise an electron from valence band to conduction band
η	Efficiency; power out divided by power in
η_{bos}	Balance of system efficiency; efficiency of inverter, battery and components other than the PV array
$\eta_{\text{bos,i}}$	Efficiency of the balance of system serving only load i, such as a transformer or rectifier
θ (degrees)	Incident angle; angle between surface normal and a line to the sun
λ (m)	Wavelength of incident light waves
ν (1/s)	Frequency of light waves
ρ	Reflectivity; fraction of sunlight not transmitted or absorbed, but rejected from the surface
σ	Stephan-Boltzmann constant: 5.670×10^{-8} W/m^{2}K4 (0.1714×10^{-8} Btu/hft2R4)
τ	Transmissivity; fraction of sunlight not absorbed or reflected, but passed through the surface
ϕ (degrees)	Latitude; angular position on the globe from the equator
ω (degrees)	Hour angle; angle of the earth's rotation away from solar noon

APPENDIX B: UNIT CONVERSIONS

Dimension	SI Unit		English Unit
Area	1 m^2	=	10.76 ft^2
Density	1 kg/m^3	=	0.06243 lbm/ft^3
Energy	1 kWh, 3.6 MJ	=	3412 Btu
Force	1 N	=	0.225 lbf
Heat transfer coefficient, U-value	1 $W/m^2/C$	=	0.176 $Btu/hr/ft^2/F$
Insolation, heat flux	1 W/m^2	=	0.3171 $Btu/hr/ft^2$
Length	1 m	=	3.28 ft
Mass	1 kg	=	2.20 lbm
Power, heat transfer rate	1 kW	=	3412 Btu/hr, 1.34 hp
Pressure	1 Pa	=	1 Pa = 0.000145 psi
Specific heat	1 kJ/kgC	=	0.239 Btu/lbm/F
Temperature	1 C,	=	F = C*9/5+32.2
Thermal conductivity	1 W/mC	=	0.578 Btu/hr/ft/F
Thermal resistance, R-value	1 C/W	=	0.527 Fhrs/Btu
Velocity	1 m/s	=	3.28 ft/s
Volume	1 m^3, 1000 l	=	35.3 ft^3, 264 gallons

INDEX