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Editor

Eco-design in Electrical Engineering

Eco-friendly Methodologies, Solutions and Example for Application to Electrical Engineering

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Contents

Introduction

This publication is positioned in the context of sustainable development, for which eco-design is a major tool for the improvement of the environmental impacts of products, services and systems. In the case of electrical equipment, the eco-design approach is also connected to the development of renewable energies and energy efficiency.

This book covers four different aspects of eco-design that apply to electrical engineering.

At first, the actual and future methodologies and standards, including regulations which apply to electrical engineering, are described. Then, Part II is devoted to energy system and planning, including insertion constraints of equipment into the grid.

Components such as transformers and cables, their eco-design characteristics and impacts, and their potential to improve environmental impacts of the network are described in Part III. Finally, Part IV deals with materials in terms of performance and ecological impact.

Part I
Methodologies and Standards

Overview of Eco-design Applications on Various Types of Electronic Product Development

Lhopital Vanessa and Bordignon Melanie

Abstract Alstom Transport Villeurbanne is a design and manufacturing site dedicated to railways signalling systems and equipment, and the Alstom Transport Center of Excellence for electronics. Villeurbanne entity has been ISO 14001 (Environmental management systems—requirements with guidance of use, 2004, [1]) certified for its design activities, and has achieved the AFAQ ISO 14006 (Environmental management systems—Guidelines for incorporating eco-design, 2004, [2]) "confirmed" level for Eco-design (3 over 4). The purpose of this paper is to present an overview of the eco-design principles application in different types of development for new electronic products destined to on-board transportation systems or sideway signalling systems.

Keywords Eco-design principles · Energy consumption · Life cycle analysis (LCA) · Product environmental impact · Functional unit · Continuous improvement · Product redesign · Type III environmental declaration · PEP ecopassport

1 Introduction

ALSTOM Villeurbanne is a design and manufacturing site for railways signalling systems and products such as electronics' train control equipment. These products are made up of mechanic parts (metallic sheets, screws, etc.…) and electronic parts (printed circuit boards, components, cables…).

For many years an environmental approach has been set up in Alstom to reduce the sites and product's impacts. In January 2014, Alstom Villeurbanne site has been recognized for its eco-design approach when renewing its ISO 14001 certification. This certification now includes the design and the development activities, i.e. the

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eco-design approach, in addition to the site activities. In that context, an AFAQ Eco-design evaluation was done, confirming a high maturity level (3 on 4) recognising the approach and methodology relevance.

The eco-design philosophy is fully embedded into the Alstom Villeurbanne New Product Development process.

2 Eco-design in Product Development Process—DFE

The development of a new product follows an internally defined strict process, based on a phase-gate system. Each development phase is reviewed with a list of criteria validating the achieved work. The list of criteria includes the product environmental impact amongst all other aspects such as technical performance, cost, industrialization, etc.

The reviews, their associated list of criteria and their applicability at each product development phase are determined by several factors:

- stage of product development
- complexness of design, redesign with re-use
- degree of freedom, especially linked with the customer specifications and overall expectations.
- etc.

The inclusion of the product environmental impact in the product design criteria is materialized through dedicated check-lists and institutionalized through the internal procedures, an approach also known as "Design for Environment".

Following each product development review, a separated eco-design review is performed, in order to assess its timely and efficient inclusion in the overall process.

More practically, eco-design "golden rules" have been developed and are run through the design steps. Depending on the previously described factors, they are used in diverse ways.

3 Application of Eco-design Principles: Case of a Global Product Architecture Design

When product design starts with global architecture choice, eco-design principles can be applied upstream, and the range of "play" is the largest. In this case, eco-design recommendations orient design to privilege modularity, interchangeability, anticipate maintenance, increase recyclability, and of course reduce energy consumption.

Eco-design principles have been applied when designing the CCP4U500 electronics rack architecture. CCP4U500 is the Controller for an Urban Railway

Signaling Platform allowing Safety Train Fleet Control and Supervision. The architecture is based on a modular design capable of adapting the equipment to different types of Urban/Mainline rolling stock. This adaptability constraint led to designing a product composed of carefully distributed devices in the train, connected together through an Ethernet network.

It has been decided to develop for this product the functionality of a "sleeping mode". During its use, the product consumes 515 W, versus 65 W in stand-by mode. With a lifetime of 20 years, an operating time of 77.9%, an annual consumption of 3516 KWh, and an active consumption 7.6 h a day, the stand-by mode allows globally savings of 54% in energy consumption.

A Life Cycle Assessment has been performed on the product according to ISO 14040 [3] and ISO 14044 [4] standards. A resulting type III communication has been published, in the frame of PEP ecopassport® program.

4 Application of Eco-design Principles: Case of a Product Design from Scratch

For designs "from a blank page", concepts and options are initially almost unlimited. Eco-design principles can be fully applied, and when only a few solutions remain, individual environmental impact assessment is performed, through a life cycle assessment (LCA) methodology, using the Environmental Improvement Made Easy (EIME©) software.

The final concept choice is driven by a sound decision-making process with a matrix integrating the environmental impact. Its contribution is defined by customer expectations in terms of environmental commitment and project specificities.

The development of the Cut Shield Cabling Adapter started from scratch. The CSCA product answers the need to cut the shields of Ethernet cables (communication network) between two cars or between two coupled trains. This cut is necessary to avoid residual currents and therefore to prevent the risk of fire, but cutting the shields has the disadvantage of reducing the network immunity to electromagnetic interference. The CSCA product's role is to ensure the protection of Ethernet network against electromagnetic interference when the shields cut is performed.

Several design options were envisioned, with differences significant enough to prevent an obvious choice. A detailed environmental impact assessment has been performed between the "design finalists". In parallel, a prototype has been built for each of the solutions. The comparative Life Cycle Analysis elected one of the concepts as highly beneficial, with significant reduction of the majority of the environmental impacts, and no impact displacement.

The other criteria, such as ease of mounting, assembly time, cost, etc. were added to the decision-making process matrix, as well as the environmental impact.

The “greenest” solution was chosen, reducing the energy consumption needed for the product manufacturing by 77%, representing an 88 MJ savings, equivalent to the energy of more than 10,000 AA rechargeable LR06 stick batteries (1.2 V).

The choice of this concept also reduced by more than 85% the product carbon footprint, amounting to almost 10 kg of CO_2, as well as water pollution by 87%, equivalent to 633 m^3 of water which would have been required to dilute toxic elements that would have been dumped into water at all stages of the product life cycle. This corresponds to the water consumption of more than 10 persons in one year (all water-use purposes considered).

In this case, eco-design principles were used to choose between design options. A type III communication has been published on this product with PEP ecopassport® program.

5 Application of Eco-design Principles: Case of a Product Development Based on a Previous Generation

For new product generations, initial environmental improvements objectives are defined based on return on experience from previously eco-designed electronic products and added to the product design specifications. In a continuous improvement approach, new generations are designed to have a significantly lower environmental impact than the previous solution performing the same function (functional unit remaining unchanged).

The IMP product is a safety block fit in traction electronics. Its function is to open the circuit breaker and to detect a malfunction as speed sensor inputs and low voltage (traction and recovery of inadvertent energy, differential current sense or invalid operation).

During the development of a new IMP product generation, a Life Cycle Assessment has been performed to determine its significant impacts & aspects and choose priority actions.

Several continuous improvement actions have been led: the latest available electronics components have been chosen and have allowed downsizing the equipment, a new sampling system has been developed to manage I/Os, a new board routing has allowed better thermal management and the suppression of heatsinks, and a debugging interface has been created to ease the functional testing and maintenance.

A comparative Life Cycle Assessment on the previous and the newly developed IMP products has shown the enhanced product has enabled an energy consumption decrease of 32% and a raw material use of 56%.

In this case, eco-design principles were used to increase a product family environmental performance. A type III communication has been published with PEP ecopassport® program.

6 Application of Eco-design Principles: Case of a Product Development with Limited Design Freedom

It can occur that eco-design principles cannot be applied upstream during a product development, or that design constraints are so high that they allow only a very limited window of action to improve the developed product environmental performance.

For these low-freedom designs, numerous elements are usually frozen at an early stage in the development. In this case, some light improvements or optimizations can be proposed.

EVC2 is an electronics rack with a safety speed-measuring mission, reading the ground beacons, assessing the actual speed when the wheels spin thanks to the accelerometer, and giving the appropriate stopping instructions.

Eco-design "golden rules" have been browsed when its design was already advanced. It has been chosen to decrease the back cover thickness, to have a mass and environmental footprint decrease. This reduction led to a weight gain of 2.4% on the mechanical parts, improving the environmental performance by $\sim$2.4% on all indicators of the EIME software on the mechanical part.

In this case, eco-design principles were applied in late design stages but could lead to a better product environmental performance.

7 Conclusion

By having dedicated environmental reviews included in the product development gates, and including environmental impact as a criterion in the design choice, Alstom Villeurbanne shows that eco-design principles can be applied in diverse cases of new electronics product development. Following this approach to choose a product architecture, to elect the best candidate between several initial concept, to develop a new generation of product, or even when the product design is already advanced, can lead in any of these applications to significant environmental improvements. For these purposes, environmental assessment, life cycle analysis and eco-design golden rules are relevant tools.

References

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Hazardous Substances Management in the Supply Chain

Christophe Garnier, Pierre Bardollet and Eric Bonneville

Abstract For decades, Schneider Electric has been committed to playing a key role in the environmental challenges we are facing. Schneider Electric has always been a step ahead in environmental protection and recognized for our environmental actions and the results in our products and activities. For our products, we closely monitor compliance with regulations and directives, and extend applications beyond geographical areas when appropriate. The purpose of this paper is to present an overview of the eco-design process implemented in the Schneider, and especially on the management of hazardous substances.

Keywords Eco-design · Hazardous substances · Supply chain · Energy · Life cycle analysis (LCA) · Product environmental impact · PEP ecopassport · Green premium · Eco label

1 Introduction

Being environmentally responsible in manufacturing can be interpreted in more than one way. On one hand, a manufacturer can claim to be "green" because its products and operations meet all the minimum requirements established by various authorities.

But we think the commitment to preserve and protect the environment—our one and only environment—must go deeper than that.

The use of chemicals in manufacturing is one area that has drawn much attention in recent years. Fortunately for manufacturers seeking to ensure the chemical substances used in their products and processes are both safe and environmentally benign, the European Union has set the bar very high in developing the Restriction of Hazardous Substances (RoHS) and Regulation on Registration, Evaluation, Authorization and Restriction of Chemicals (REACh) requirements.

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2 No Bad Ingredients

The Restriction of Hazardous Substances (RoHS) directive prohibits the use of six specific substances, plus four types of phthalates, that until recently were commonly used in other electrical equipment. However, RoHS requirements differentiate between electrical and nonelectrical equipment, and manufacturers can take advantage of numerous exemptions. For example, small amounts of lead are acceptable in specific applications, even though lead is one of the six hazardous substances singled out by RoHS.

We view the current RoHS requirements not as minimum requirements, but rather as leading the way for the world's future collective health and welfare. Therefore, our goal is to not include any substance identified by RoHS as being hazardous in any of our products. That means we do not take advantage of the additional allowances offered for nonelectrical equipment and, insofar as possible, we want to avoid exemptions.

Even though RoHS compliance is absolutely required only for products made or sold in the European Union, we recognize that RoHS provides the strictest environmental regulation of this type in the world. Therefore, we apply this same approach to all of our products worldwide, which means everyone benefits.

3 No Bad Chemicals, Either

With the passage of the Regulation on Registration, Evaluation, Authorisation and Restriction of Chemicals (REACh) in 2007, manufacturers became directly responsible for guarding against the effects of chemical use. This covers both chemical ingredients and chemicals used in the manufacturing process, such as for cleaning or rinsing, but also chemicals in manufactured articles. Of the 14,000 chemicals now registered in the REACh database, 169 already are considered "substances of very high concern" (SVHC), and that list continues to grow.

Again, we view our compliance with REACh requirements as more than just minimally acceptable behavior. For example, the program is primarily based on declarations made by each manufacturer. As such, it also permits inclusion of SVHC in products, to some extent, as long as its inclusion is noted in the product declarations. Rather than take advantage of this, we decided to go beyond that requirement as well. As soon as a "substance of concern" comes under official consideration as a possible SVHC, we trace the potential presence. As soon as it is submitted to specific authorization, we substitute that chemical anywhere it has been used as soon as possible, and we ban its further use in any of our products and processes. As with the RoHS requirements, this is also something we do on a global basis.

4 Being Selective in Material Use

Of course, there are many other material choices to be made in manufacturing beyond those specifically covered by RoHS and REACh, and environmentally friendly material selection is another area of concern. For many years we have tried to make material selection decisions in a similarly environmentally friendly way, remembering that the local environment is also important. For example, many of our products have fire protection requirements. A decade or more ago, we consciously decided to avoid the use of toxic flame retardants in our products, which benefits all involved.

We also design our products to incorporate recycled and biomass materials—such as plastics made from biomass rather than from oil—as much as possible. That's good for the environment, but we are going even further in a move designed to improve personnel safety: Instead of thermosetting materials, we're moving toward a wider use of thermoplastic materials, which are totally inert. This will mean workers will have far less exposure to potentially hazardous reactive chemistry. As an example, some medium voltage parts that historically were made using thermoset polyester plastics are now manufactured in high-performance thermoplastic.

Schneider Electric Green Premium™ ecolabel program, launched in 2012, provides an easy and convenient way for customers and end users to quickly confirm the level of each of our products' overall environmental compliance. For more information, http://www.schneider-electric.com/green-premium.

5 How to Track Substances Content?

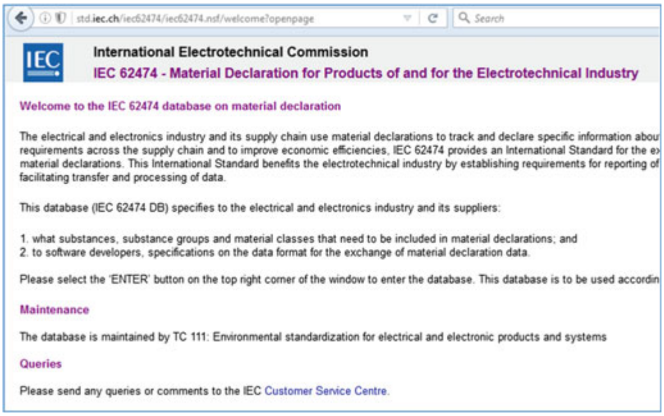
There are many substances regulations worldwide, covering different substances, or groups of substances. Using the substances names, it is sometimes not easy to check if different regulations apply to the same substances, cover the same groups of substances,…

Also, each manufacturer, or industry, have their own list of substances they manage. And each list can be in different formats: text, table, database,…

At the end, it is a nightmare to collect information through the supply chain.

This is why the IEC has developed a standard for the electric and electronic industry that standardize a list of substances with unique names, and a unique declaration format so that all lists can be transmitted in the supply chain, and aggregated.

This standard is IEC62474, it is made of 2 parts:
The standard itself
A database containing the minimum list of substances to declare so that compliance with any substance regulation can be assessed
The list of substance is freely available at http://std.iec.ch/iec62474.


std.iec.ch/iec62474/iec62474.nsf/welcome?openpage
Search
IEC
International Electrotechnical Commission
IEC 62474 - Material Declaration for Products of and for the Electrotechnical Industry
Welcome to the IEC 62474 database on material declaration
The electrical and electronics industry and its supply chain use material declarations to track and declare specific information abou
requirements across the supply chain and to improve economic efficiencies. IEC 62474 provides an International Standard for the ex
material declarations. This International Standard benefits the electrotechnical industry by establishing requirements for reporting of
facilitating transfer and processing of data.
This database (IEC 62474 DB) specifies to the electrical and electronics industry and its suppliers:
1. what substances, substance groups and material classes that need to be included in material declarations; and
2. to software developers, specifications on the data format for the exchange of material declaration data.
Please select the 'ENTER' button on the top right corner of the window to enter the database. This database is to be used accordin
Maintenance
The database is maintained by TC 111: Environmental standardization for electrical and electronic products and systems
Queries
Please send any queries or comments to the IEC Customer Service Centre.

Home page of the IEC 62474 project

SubstanceGroup	SpecificSubstance	CASnumber
	Diarsenic pentoxide	1303-28-2
	Diarsenic trioxide	1327-53-3
Asbestos	See Reference Substance workshee	See Reference Substance workshee
Azocolourants and azodyes which f	See Reference Substance workshee	See Reference Substance workshee
	Beryllium Oxide	1304-56-9
	Boric Acid	10043-35-3, 11113-50-1
Brominated flame retardants (other t	See Reference Substance workshee	See Reference Substance workshee
Brominated flame retardants (other t	See Reference Substance workshee	See Reference Substance workshee
Cadmium/Cadmium compounds	See Reference Substance workshee	See Reference Substance workshee
Cadmium/Cadmium compounds	See Reference Substance workshee	See Reference Substance workshee
Chromium (VI) Compounds	See Reference Substance workshee	See Reference Substance workshee
	Cobalt dichloride	7646-79-9
Dibutyltin (DBT) compounds	See Reference Substance workshee	See Reference Substance workshee
Dioctyltin (DOT) compounds	See Reference Substance workshee	See Reference Substance workshee
	Dimethyl Fumarate (DMF)	624-49-7
Disodium tetraborates	See Reference Substance workshee	See Reference Substance workshee
Fluorinated Greenhouse Gases (PF	See Reference Substance workshee	See Reference Substance workshee
	Formaldehyde	50-00-0
Hexabromocyclododecane (HBCDD	See Reference Substance workshee	See Reference Substance workshee
Lead/Lead Compounds	See Reference Substance workshee	See Reference Substance workshee
Lead/Lead Compounds	See Reference Substance workshee	See Reference Substance workshee

IEC 62474 List of substances by names and CAS Number

TypicalApplications	Basis	BasisDescription	ReportableApplications	ReportingThreshold
Additive in wood, metal, glass and p	Criteria 1: Currently Regulated	Candidate list for European REACH	All	0.1 mass% of article
Additive in wood, metal, glass and p	Criteria 1: Currently Regulated	Candidate list for European REACH	All	0.1 mass% of article
Insulator, filler, pigment, paint, talc	Criteria 1: Currently Regulated	ANNEX XVII of REACH Regulation (I	All	Intentionally added
Pigment, dyes, colorants	Criteria 1: Currently Regulated	ANNEX XVII of REACH Regulation (I	Textiles and Leather	0.003% by weight of the finished tex
Ceramics	Criteria 3: For Information Only	European Industry Agreement (DIGI'	All	0.1 mass%
In wood veneers/ pressed wooden p	Criteria 1: Currently Regulated	Candidate list for European REACH	All	0.1 mass% of article
Flame retardant in printed wiring boa	Criteria 3: For Information Only	Industry Standards IEC 61249-2-21	Printed wiring board laminate	0.09 mass% total bromine content i
Flame retardant for housing, connec	Criteria 3: For Information Only	Joint JEDEC/ECA JS-709A Standar	Plastic materials except printed wiri	0.1 mass% of bromine in plastic ma
Pigments, anti-corrosion surface tre	Criteria 1: Currently Regulated	2011/65/EU (EU/RoHS Directive anc	All, except batteries	0.01 mass% of total Cd in homogen
Relay contact; photodiode voltaic ce	Criteria 1: Currently Regulated	2006/66/EC EU Battery Directive an	Batteries	0.001% by weight of battery
Pigment, paint, ink, catalyst, plating	Criteria 1: Currently Regulated	2011/65/EU (EU/RoHS Directive anc	All	0.1 mass% of total Cr+6 in homoge
Pneumatic panels to indicate water	Criteria 1: Currently Regulated	Candidate list for European REACH	All	0.1 mass% of article
Stabilizer for PVC, curing catalyst fc	Criteria 1: Currently Regulated	ANNEX XVII of REACH Regulation (I	All	0.1 mass% of tin in the part
Stabilizer for PVC, curing catalyst fc	Criteria 1: Currently Regulated	ANNEX XVII of REACH Regulation (I	(a) textile and leather articles intend	0.1 mass% of tin in the part
Biocide, mold prevention treatment (	Criteria 1: Currently Regulated	COMMISSION DECISION 2009/251.	All	0.00001 mass% of the part
In wood veneers/ pressed wooden p	Criteria 1: Currently Regulated	Candidate list for European REACH	All	0.1 mass% of article
Refrigerants, blowing agents, exting	Criteria 1: Currently Regulated	EU Reg. No. 842/2006	All	Intentionally Added
Textiles	Criteria 1: Currently Regulated	Lithuanian Hygiene Norm HN 96:20(	Textiles	0.0075 mass % of textile

In what product the substance is used, reason for including the substance in the list, minimum threshold for declaration.

The database is updated as soon as a substance is expected to be regulated, allowing users of the standard to update their requirements towards suppliers.

6 Schneider Electric Eco Label: Green Premium

Our ambition is to address potential impacts through **every phase of our products' life cycles**. This means addressing product manufacturing and the related resource extraction, transportation throughout the value chain to end-users, installation in specific processes and operations, usage, and additional impacts created during product disposal, recycling, and/or degradation. The last life cycle stage is considered by the EEE industry to be an important issue to be addressed, especially with regard to both the impacts associated with hazardous substance emission and the potential for a circular economy, which would lead to resource preservation and an overall reduction of environmental impacts, including climate change.

Another organizational issue identified is **customer access to environmental information** so that buyers can have complete confidence in the specific product as well as in their ability to use the information as part of their own sustainability initiatives. This brings incremental value to companies at all stages of their supply chains. The only way businesses can comply with regulatory and consumer pressure is through comprehensive knowledge of the products and materials they use, and by making the right business decisions with that information. Access to sustainability information is critical to a company's long-term growth and product strategy.

Given these considerations, our ecolabel has been built on the following objectives:

Ensure our partners and customers that the use of **hazardous substances** in products is being **managed with awareness**, aiming for a **reduction to a minimal level**;

Provide detailed, transparent and reliable **data** on products' **environmental impacts** across the life cycle, with complementary criteria;
Help users to **manage the end of life** of products by maximizing **reuse of components** and **reducing the related hazards** and **environmental impacts**.

How the Green Premium ecolabel covers environmental issues

7 Communication Using the PEP: Product Environmental Profile

The environmental impacts of Schneider Electric products are communicated to the customers and stakeholders through a PEP (product Environmental Profile). This document, based on ISO 14025, presents all environmental information through the complete life cycle of the product.

The PEP are managed by a Program Operator. Schneider Electric selected the "PEP ecopassport" organization.

Purpose	Approach of the PEP program
To the market demand	• Program certified ISO 14025 • Declaration based on a product LCA • Third party verification mandatory
Development of rules for a product category (PSR)	• Proposal of creation to the Steering Committee • Development in an open working group • Critical review of the PCR/PSR mandatory • Registry and accessibility thru the program website
Publication of a declaration	• Cover 1 product, an homogeneous product family or a typical product from a group of industrials • Comply with technical and editorial rules of the program PEP • Verified by an accredited verifier
Market of destination of a declaration	• For the construction, infrastructures and industry • Visibility recognition and international usage

8 Conclusion

The knowledge of the content of the components a manufacturer is being is key to have a precise information about the final product.

The first objective is to allow an exact substance assessment to ensure compliance with substances regulations. But that also allows to go be yond mandatory requirements by voluntary removal of some substances, or replacement of substances by more environmentally friendly substances. This can be done by applying an EcoDesign policy at the early stage of the product development. The final environmental footprint, and environmental benefits of the products can be communicated to the market and the customer through the Green Premium program, and Product Environmental Profiles.

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4. ISO 14020:2000, Environmental labels and declarations—General principles
5. ISO 14024:1999, Environmental labels and declarations—Type I environmental labelling—Principles and procedures
6. ISO 14025:2006, Environmental labels and declarations—Type III environmental declarations—Principles and procedures
7. ISO 14040:2006, Environmental management—Life cycle assessment—Principles and framework
8. ISO 14044:2006, Environmental management—Life cycle analysis—Requirements and guidelines
9. ISO 14062:2002, Environmental management—Integrating environmental aspects into product design and development
10. ISO 14001:2004, Environmental management systems—Requirements with guidance of use
11. ISO 14006:2011, Environmental management systems—Guidelines for incorporating eco-design

SWOT Analysis of the ISO 14006 Application. A Practical Case and Its Consequences on Ecodesigned Products

Mélanie Bordignon and Vanessa Lhopital

Abstract Alstom Transport Villeurbanne is a design and manufacturing entity dedicated to railways signalling systems and products. Villeurbanne entity has been ISO 14001 [1] certified for its design activities, achieving the level 3 over 4 on eco-design evaluation ("AFAQ ecoconception" method). The purpose of this paper is to illustrate ecodesign approach launched in Alstom Villeurbanne for many years by presenting a return on experience concerning several topics: environmental analysis, processes, technical application, stakeholders and budget.

Keywords Environmental management system (EMS) · ISO 14001 · ISO 14006 · SWOT · Continuous improvement · Life cycle assessment (LCA) · Environmental analysis · Return on experience (REX)

1 Introduction

ALSTOM Villeurbanne is a design and manufacturing site for railways signalling systems and products such as electronics' train control equipment. These products are made up of mechanic parts (metallic sheets, screws, etc.…) and electronic parts (printed circuit boards, components, cables…).

For many years an environmental approach has been set up in Alstom Transport to reduce the sites and product's impacts. In January 2014, Alstom Villeurbanne site has been recognized for its ecodesign approach when renewing its ISO 14001 [1] certification. This certification now includes the design and the development activities, i.e. the ecodesign approach, in addition to the site activities. In that context, an AFAQ Ecodesign evaluation was done, confirming a high maturity level (3 on 4) recognising the approach and methodology relevance.

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2 ISO 14006 Principles and Steps

ISO 14006 [2] is a guideline to put in place eco-design as part of an environmental management system.

The following steps have to be followed and implemented:

(1) Determination of significant aspects/impacts, (2) definition of the applicable requirements, (3) setting of objectives, targets and program (4) check skills and plan training, (5) internal & external communication, (6) writing of documents to constitute the management system, (7) insure detailed planification for action on new products, (8) operational control on designs, (9) internal audit for continuous improvement, (10) management review of the EMS.

3 EMS in Place

The following paragraphs are focusing on certain steps of the EMS deployment, constituting Villeurbanne return on experience.

3.1 Environmental Analysis

An environmental analysis method was created to conclude on significant aspects/impacts. This method is based on life cycle assessment results, and was carried on a very representative product from Villeurbanne's catalogue. Taking also into account aspects not given by the life cycle tool (such as noise, electromagnetic compatibility…), the study gave score for aspects/impacts couples, that were weighted according to a marketing approach, customer requirement, feasibility, and regulation compliance.

The conclusion for the embedded electronic products was the following:

- High importance of energy efficiency during use phase due to electrical consumption of electronic devices
- Medium importance of material use in manufacturing phase due to use of rare and precious material in electronic boards.

3.2 Processes and Operational Control

The design processes of Alstom products were reviewed to integrate ecodesign. Hardware processes now integrate 2 ecodesign reviews, during specification gate review and detailed architecture gate review. The objective is to first determine environmental targets and design rules to improve the performance, and then to evaluate, with a LCA approach the environmental performance of the different concepts, to choose the best. When ecodesign is in balance with other aspects (quality, cost, technical performance, mounting constraints), the final decision is taken according to a decision matrix process.

This approach was applied on different new designs. The results obtained are described in the following paper "**Overview of Ecodesign applications on various types of electronics product development**". For some products, the eco-design application led to a publication in PEP ecopassport© program.

3.3 Continuous Improvement and Targets Setting

The return on experience concerning:

- the efficient ecodesign principles (golden rules)
- the percentage of decrease in environmental impact obtained
- the control of the impact displacement risk helped to better set targets for future developments in management review. The generic objective for each design is now the following:

The comparison shall be done according 10 indicators given by the EIME© software and all the indicators shall have the same weight: 1. The characterization of the environmental improvement shall be measured making the average of all the improvements, indicator per indicator and to be acceptable the improvement shall be at least: −10%.

For natural resources, energy depletion and global warming, it is not allowed to have a degradation of the performance. It is also possible to have a specific target, based on voluntary decision (platform position of customer specific request).

4 SWOT Analysis

The ISO 14006 [2] principles setting which began in 2012 were awarded by a certification in 2014, and led to a significant return on experience on different themes:

4.1 On Environmental Analysis

Strengths: It is a methodological step by step approach, based on LCA and taking into account customer requirements. It is already recognized as a strong point by auditors.

Weaknesses: The skills on LCA realization shall be strong and it remains difficult to assess aspects not taken into account by LCA tool (semi quantitative approach).

Opportunities: As the environmental analysis method is well established, it has now a better recognition of the results and can be deployed on other Alstom activities (trains and other sub-systems).

Threats: The results shall be reviewed periodically and the cut criteria are for the moment defined arbitrarily.

4.2 On Processes

Strengths: Integration into processes is in line with quality requirements, the ecodesign gates are mandatory, the customer requests are considered and the regulatory watch is in place.

Weaknesses: “Written” does not mean “applied”. A regular review is necessary due to documentation evolution and company organization moving. Application of regulation watch and compliance represent a high workload.

Opportunities: Processes are not for Villeurbanne site only, but also for other electronic entities. It may push for ecodesign application in other sites.

Threats: The internal process does not cover products developed on specification, for which another approach is necessary (with suppliers). The process at a higher level (for global train electronic architecture) is still to be covered.

4.3 On Technical Topic

Strengths: Robust tools are in place and new tools are emerging (golden rules, LCA software, assessment method, regulatory watch). A communication strategy is defined for the results (PEP ecopassport©).

Weaknesses: Development cycle is long in railways (long time to have REX). Capacity to innovate in the design is limited because of use of standard parts.

Opportunities: Ecodesign approach is a leverage for innovation, golden rules are enriched progressively by the REX. Ecodesign ideas involve many actors (mechanic, thermal, hardware engineers).

Threats: Difficulties to push for new ideas in case of redesign (because a part of the design is kept).

4.4 Concerning Stakeholders

Strengths: Roles and responsibilities are defined. Skills are covered with a training plan. Stakeholders are defined, and management is involved (thanks to the management review). Steering committee members are pushing for the topic.

Weaknesses: Activity is seen as a new constraint. As it is new, there is a high need to promote it by internal communication. Customer recognition of the approach is sometimes uncertain (because of new approach and new standard).

Opportunities: Stakeholders can be actors of ecodesign ideas. Villeurbanne maturity can also help customer to progress on knowledge (green washing avoided).

Threats: AFAQ evaluation is not well known in railway sector. Sometimes tenders do not consider EMS.

4.5 On Budgets

Strengths: Budget consideration is requested by ISO standards and shall be in accordance with resources. Objectives, targets and program have to be in accordance with available resources. KPI are created and monitored for budget follow-up.

Weaknesses: Complete deployment of the EMS has a high cost. Audit preparation and execution is time consuming. Processes follow-up is heavy.

Opportunities: A systematic budget is awarded to hold the EMS. Management committee helps to obtain the budget (higher involvement).

Threats: ROI is difficult to calculate on an EMS.

5 Conclusion

Inclusion of ecodesign as part of an environmental system is a long process, requiring resources, time and skills. A setting of environmental analysis needs a deep thought but output is very important to set priority actions. Management involvement is progressive and helps to make resources and budget match with the workload. Integration of ecodesign in processes is done first at product level, and then at system level. First operational control on new designs is a real test to implement ecodesign golden rules and their consequences on the environmental impacts. Then, return of experience can be taken into account to set realistic targets for future designs. All these steps shall be escorted with a strong communication to insure internal stakeholder's collaboration. Concerning external communication, a strategy has to be defined for environmental declaration. This strategy has to be discussed with customer to make it well understood and to prevent green washing.

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Network for Building Purposes Equipment Environmental Declarations—Towards a Harmonised System?

Etienne Lees-Perasso, Julie Orgelet, Damien Prunel and Axel Roy

Abstract Throughout Europe, the increasing demand on performance proofs from public bodies, construction leaders and end customers motivates manufacturers to communicate on the global environmental performance of their products. In parallel, there is a strong willingness of data transparency and credibility, so that accredited standardisation organisations have been working on defining more restrictive rules for the display of the environmental impacts of products. Several ways exist to answer this need: type III environmental labelling (FDES, IBU, EPDs for the building equipment, PEP Ecopassport® programme for the EEE. However, methodological differences remained a limitation to assess the global life cycle impact of a building. There is now a common framework with the new EN 15804:2012 standard. It sets PCR for EPDs related to building products (building materials, EEE and climatic engineering products). Its implementation aims at harmonizing the different methodologies developed in Europe for communicating on environmental performances of building products. This standard has been notably used in French regulation through the decree. Similar regulations are under study in Belgium and Spain. Though, some discrepancies remain, and some difficulties arise specifically for the EEE sector. The main problem to be addressed is that this standard is mainly expressed for the building material world and not the EEE sector; this is thus a sectorial problem. The building equipment and EEE

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sectors are quite different in terms of materials, processes and logistic chains. Secondly, there is also a lack of common standards giving a frame for environmental issues. Finally, the exploitation of results from EEE environmental declarations can be difficult. The notion of study perimeter, functional/declared unit and reference service life time are different in the two sectors. Therefore, how to compare two products set by a declared unit while they do not work the same amount of hours? For instance, two different types of EPDs in compliance with the EN15804 can make the comparison possible between two luminaires (IBU). As the first EPD does not inform the same number of operational hours as the second does, it remains impossible to find a common basis from which comparing these luminaires. Some global issues also remain. The different applications of the EN15804 so far have led to divergences in terms of comprehension of the standard and to the addition of specific requirements. A declaration established in one country is not necessarily usable in another one. In order to overcome those difficulties, a European-wide non-profit organization, the Eco Platform, is currently working on ensuring mutual recognition and compatibility between programs and regulations. Their work gathers European environmental program members and users in order to discuss and solve the issues. Another approach that might lead to a better harmonisation is the upcoming building LCA and environmental declarations. As architects and contractors in the building sector will perform LCA of whole buildings, they will use building equipment environmental declarations. Compatibility and modularity of those assessments will then become a strong requirement, and the declarations conforming to those principles will have an advantage during the suppliers and materials selection. Therefore the market could shift due to this incentive and the contractors could define the required format de facto. On a larger scale, actual harmonization works are in progress to limit the differences between the EN15804 standard and the PEF/OEF guidelines. The outcome of this work is still uncertain. In conclusion, there used to be no common framework for the building product EPDs in Europe. The EN15804 standard has provided a first step into this harmonization. It has, and it will replace as it goes along previous formats of documentation. Nevertheless, it has appeared that this standard still doesn't lead to a full compatibility between declarations, notably in the EEE sector, and does not allow the use of compatible declarations to globally conduct the LCA of a building yet. But the harmonization is still ongoing with the Eco Platform work and EN 15804 standard evolution, and the environmental program declaration as well as the regulation might evolve within the next few years. This evolution may possibly bring new difficulties along a better harmonization. In this context, it is important for EEE sector companies performing LCA and environmental declaration to keep up to date with the latest evolutions so to anticipate the future regulatory and market needs.

Keywords Environmental declarations · Standards · Life cycle assessment

1 Introduction

Throughout Europe, the increasing demand on performance proofs from public bodies, construction leaders to end customers motivates manufacturers to communicate on the global environmental performance of their products. In parallel, there is a strong willingness of data transparency and credibility, so that accredited standardisation organisations have been working on defining more restrictive rules for the display of the environmental impacts of products.

A first level of answer is the type III environmental labelling described by the ISO[1] 14025 standard [1]. From a European point of view, FDES[2] and IBU[3] formats are examples of type III declarations for building products. Swedish EPDs[4] are environmental declarations for all kinds of products supported by the Swedish Environmental Management Council. Finally, PEP Ecopassport® programme[5] is managing the scheme for EEE[6] environmental declarations, mostly developed in France. However, the methodological differences between all of them, knowing that they fulfill the requirements set by the ISO 14025 series, remained a brake to assess the global life cycle impact of a building [2].

As it can be understood from above, there used to be no common framework as regards as Building EPDs. For instance, FDES and PEP Ecopassport® did not present the same approach, targets and set of indicators. Nevertheless, both of these programs have had to drag towards a common approach in compliance with the new EN 15804:2012 standard [3]. It sets PCR[7] for EPDs related to building products (building materials, EEE and climatic engineering products). Its implementation aims at harmonizing the different methodologies developed in Europe for communicating on environmental performances of building products. It specifies among others system boundaries, calculation methodologies of environmental and flow indicators [4]. The challenge is thus to apply this new standard for EEE.

This standard has been notably used in French regulation through the so called DHUP decree [5], making the use of this standard compulsory for many building equipment environmental declarations, including EEE ones. Similar regulations are under study in Belgium and Spain. Though, some discrepancies remain, and some difficulties arise specifically for the EEE sector. Consequently, which types of complements are necessary to implement the EN 15804 standard for Electronic and Electrical Equipment?

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[1]International Organization for Standardisation.

[2] «Fiches de Déclaration Environnmentales et Sanitaires» standing for Environmental and Health Declaration Formats.

[3]"Institut Bauen und Umwelt" standing for Institute Construction and Environment.

[4]Environmental Product Declaration.

[5]Product Environmental Profile.

[6]Electronic and Electrical Equipment.

[7]Product Category Rules.

2 Different Challenges to Be Overcome for the EEE Sector

This chapter aims at identifying the main obstacles to be overcome so to apply the EN 15804 standard for EEE declarations. The main problem to be addressed is that this standard is mainly expressed for and by people from building material world; this is thus a sectorial problem. For building materials, there are usually less materials, processes and sub-contractors involved for manufacturing the product, the life cycle variability is not as important as for EEE (as implementation scenario described for instance in the French DTU[8]); there is thus a better knowledge of life cycle parameters that influence the product environmental impact. That is unfortunately not the case for EEE, as there is a multimaterial approach and a widely extended use of subcontracting manufacturing phases of components or sub-assemblies to international providers. This fact is emphasized by the difficulty for manufacturers to get access to information with plenty of suppliers and intermediaries in such an international context.

As it is often the case when dealing with numerous industries, sectors and competitors, there is a lack of common standards giving a frame for environmental issues. It should harmonize EPD and make it more accessible by industrials. As a consequence, environmental information can be more easily compared, irrespectively of the countries, or the format of documentations.

Finally, the third main category of problems concerns the exploitation of results. Intrinsic characteristics of the standard pose a problem as regards as its application for EEE, especially for results interpretation. There are commonly three types of perimeters based on LCA, grouping different steps, proposed by the standard. The only mandatory perimeter is from cradle to gate (from step A1 to A3). Then, the EN 15804 gives the ability to choose between a functional (as presented in the ISO 1404X series) and declared unit.[9] There is no longer a performance dimension which can be a drawback as regards as the comparison of several products [3, 4]. Then, this standard introduces the notion of Reference Service Life, i.e. an estimated lifespan for a product. However, this notion should refer to the ISO 15686 standard which does not take into account EEE. Last but not least, this standard introduces different statuses concerning the end-of- life of waste and the D module, aiming at informing the eventual benefits and charges from recycling [6].

As it can be guessed from above, there are cross-sectorial and standard intrinsic problems that need to be addressed in order to apply the EN 15804 for EEE. This can be overcome thanks to the creation of a complementary documentation to support EEE environmental declaration. This documentation could be considered as complementary Product Category Rules (PCR).

Then another problem arises: how to compare two products set by a declared unit while they do not work the same amount of hours? For instance, two different

[8]"Document Technique Unifié" standing for Unified Technical Document.

[9]Declared unit: quantity of a construction for use as a reference unit in an EPD for an environmental declaration based on one or more information modules [3].

types of EPDs in compliance with the EN15804 can make the comparison possible between two luminaires (IBU) [7, 8]. As the first EPD does not inform the same number of operational hours as the second does, it remains impossible to find a common basis from which comparing these luminaires. If we consider that the Builder knows the type of lighting he wants (illumination level, light colour…) then he will need to compare luminaire systems that are sums of EPD and complementary information. A need to describe the parameters of energy consumptions appears, informing for instance the lifespan, the power absorbed in a given mode of use, etc. [9]. In this way, the two previous luminaires can be part of a luminaire system that is configured by the light designer who is assessing the Luminaire system LCA.

3 Towards a Better Harmonisation

The different applications of the EN15804 so far have led to divergences in terms of comprehension of the standard and additional specific requirements to each environmental program and regulation. For instance, the French DHUP decree has two additional impact indicators. Those differences still lead to incompatibility within the European environmental declaration global scheme: a declaration established in one country is not necessarily usable in another one.

In order to overcome those difficulties, a European-wide non-profit organization, the Eco Platform, is currently working on ensuring mutual recognition and compatibility between programs and regulations. Their work gathers European environmental program members and users in order to discuss and solve the issues. Though, while it aims at ensuring the harmonisation of building equipment declaration, it does not specifically take into account the EEE sector, therefore it might not address the abovementioned problematics.

Another approach that might lead to a better harmonisation is the upcoming building LCA and environmental declarations. As more and more architects and contractors in the building sector will want to, or will have to perform LCA of whole buildings, they will use building equipment environmental declarations. Compatibility and modularity of those assessments will then become a strong requirement, and the declarations conforming to those principles will have an advantage during the suppliers and materials selection. Therefore the market could shift due to this incentive and the contractors could define the required format de facto.

On a larger scale, actual harmonization works are also in progress to limit the differences between the EN15804 standard and the PEF/OEF (product/organisation environmental footprint) guidelines/ILCD recommendations. Though as the requirements differ widely, and due to the fact the PEF/OEF rules are still undergoing a pilot phase, the outcome of this work is still uncertain. The use of indicators in perpetual update and translating different stakes will raise some problems as well. In addition, the use of indicators recommended by ILCD engenders some difficulties in regard to the synchrony between indicators and EPDs updates. A lack of precision (geographical differentiation) may also jeopardize some environmental aspects such as eutrophication (water eutrophication vs. fresh and marine water eutrophication), acidification or water depletion.

4 Conclusions

There used to be no common framework as regards as Building product (equipment and EEE) EPDs in Europe. The EN15804 standard has provided a first step into this harmonization. It has, and it will replace as it goes along previous formats of documentation. Nevertheless, it has concretely appeared that this standard still doesn't lead to a full compatibility between declarations, notably in the EEE sector, and does not allow the use of compatible declarations to globally conduct the LCA of a building yet.

But the harmonization is still ongoing with the Eco Platform work and EN 15804 standard evolution, and the environmental program declaration as well as the regulation might evolve within the next few years. This evolution may possibly bring new difficulties along a better harmonization.

In this context, it is important for EEE sector companies performing LCA and environmental declaration to keep up to date with the latest evolutions so to anticipate the future regulatory or market needs.

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Dynamic Eco-design Strategic Options for Electric-Electronic Industry

Feng Zhang, Maud Rio and Peggy Zwolinski

Abstract Today industries from the electric and electronic sector are facing the challenge of improving the environmental performance of the product (eco-design). Various corporate attitudes and their related policy conduct industries to launch different solutions for eco-designing their product and services. Various strategic needs for environmental improvements therefore emerge. In addition important amount of eco-design methods are available. The challenge of planning which eco-design method to be used for a specific need is thus considerably increasing over time. This research therefore aims at providing a mechanism to generate some relevant eco-design options or some sets of methods for answering to the specific corporate orientations chosen. Existing eco-design methods used in the electric-electronic sector have been carefully analyzed and various 'interactions' between the actions followed in those methods have been identified. From this analysis, this research provides a new network of eco-design actions allowing company to explore different solutions and roadmaps for reaching concrete eco-design requirements. The company is able to select the solutions that best follow its eco-design needs depending on its specified strategic constraints and their dynamic operational context. Meanwhile, a framework was proposed to guide the company to consider these different eco-design options within its specific context. This method has been used on a case study, which has demonstrated that its ability to efficiently support the company in reaching eco-design goals.

Keywords Eco-design · Electric and electronic · Environmental management

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1 Introduction

Today, electrical and electronic industry is facing some serious environmental challenges. With the deepening of the eco-design popularity, especially at a stage of continuing concern with environmental pollution, the eco-design has been gradually embedded into the macro-development plan of the enterprise. In other words, the eco-design strategy does not only lead to independent environmental improvements, but also creates important opportunities to support the corporate sustainability covering the ecologic and economic aspects. However the diversity of the corporate requirements raises up the following question: **within the different strategic needs for corporate development, especially, the different positioning of environmental responsibilities, does the strategic choice of eco-design need to be defined in different forms? If yes, which forms of eco-design is the best?**

This article illustrates the diversity of eco-design strategic choices for given specific corporate needs. This research is based on existing and available theoretical and technical frameworks for conducting eco-design activities from academic and industrial publications and procedures. This diversity allows combining different tactical behaviors, and this may bring a variety of implementation effects. In the first planning phase, a full consideration about this diversity of eco-design strategic options is required to optimize the emergence of an optimal eco-design strategy for different business needs and backgrounds.

In the following sections, this paper firstly clarified (1) if a large number of different eco-design solutions (i.e. embodiments) for a specific environmental problem are already available and (2) if and how the diverse business needs, and the different backgrounds affect the definition of relevant eco-design patterns for those contexts. Based on this investigation (1–2) the authors recommend introducing the diversity of eco-design embodiments options in the early stage of the strategic decision-making. The strategic needs, and especially, their harmonization with other corporate tendency, as well as the integration of past environmental achievements are considered together at the beginning. This paper furthermore demonstrates the integration of diverse eco-design strategic options supports the company to find out an innovative and adaptive roadmap for its business sustainability.

2 The Vast Numbers of Eco-design Embodiments Provides a Robust Analysis of Specific Environmental Problem Considerations

Within 30 years of development, a vast number of eco-design methods and tools have been developed for answering to multiples environmental demands [1, 11]. Still today, more and more environmental aspects are treated by new eco-design methods, supported by software (e.g. LCA for life cycle assessment). These solutions include life cycle analysis methods, covering different life cycle stages, and some methods that is aiming for different purpose, such as “design for X”, where X stands for: disassembly, improving the recyclability, material selection, optimizing the use and treatment of natural resources, etc. In 2010 [7] has collected more than 500 scientific contributions covering different problems faced only during the recovery process. Facing the vast numbers of methods, a first question would be: “does the link between the environmental aspect and method can be absolute”. In other word, “does a concreted environmental topic could be achieved by using different kinds of eco-design methods?” In fact, the answer is yes. For example, to answer the requirements of WEEE directive and to optimize the recyclability of EE product, beside of the classic method of “design for recyclability”, lots of others are always available, such as the “design for disassembly”, “design for remanufacturing” and “design for material selection”. Here, the different methods used could be considered as the different strategic options. In addition, due to the informational interactions between different eco-design methods, some part of a method can be directly used in another one. For instance example is that “design for disassembly” can then embed “design for recyclability” methods to take the recyclability of the parts disassembled. Meanwhile, the typical example is the eco labeling system. Eco-labeling methods propose efficient ways to communicate the environmental performance of a product. But several authors indicated that although the communication is out of the scope of the product strategy, the criteria of eco-labeling can still be directly used as a creditable checklist for guiding the eco-design [6]. In this example, the final result of this method is not useful. Only the intermediate information are picked out and valorized.

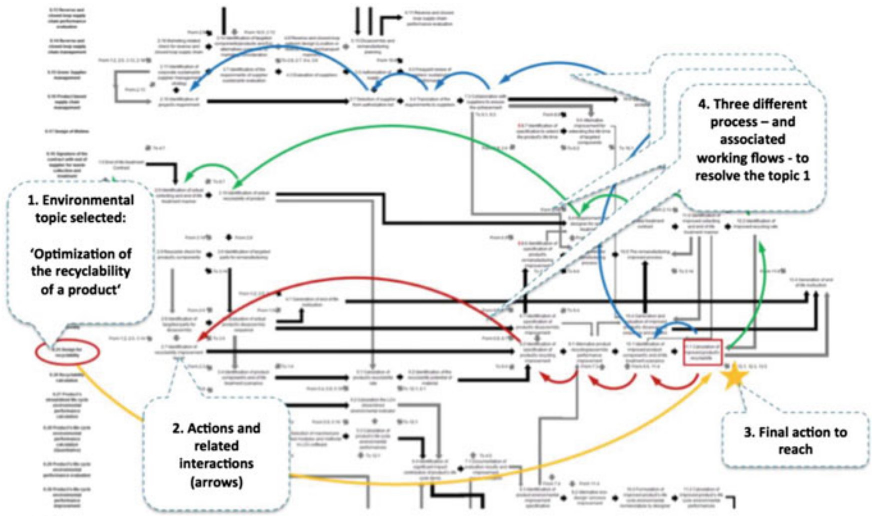
However, if the research scope is broadened from the pure product design to the whole corporate activities, this kind of interactions becomes ubiquitous. An example can be taken from the duplex links between the product LCA and the classic environmental management system-EMS ISO 14001. The results of the environmental review of EMS might generate a particular specification of product eco-design, because the material inputs and the tooling used in factories have been decided by the design. In this case, eco-design is no longer for a classic improvement of the product performance, but for the optimization of the production process. So, instead of being the classic LCA inventory the results of environmental review of EMS becomes the main input to launch the eco-design process. Inversely, the primary data from manufacturing site and the real environmental improvements furthermore optimize the data quality of eco-design and encourage innovation. Similar examples have been collected. Zhang [14] indicated for instance several interactions between different methods for designing, manufacturing, purchasing, and the communicating. In [12] seven cases are summarized pointing out that the product environmental innovation can be considered as an additional, nonetheless important, performance metric for organizational environmental management system.

The above discussion indicated that all environmental options (i.e. methods) are not independent. Answering to a strategic need could require the combination of different methods. The relevance of this combination could as well optimize the data quality, and the performance of eco-designing. A systemic analysis of environmental methods was therefore released by Zhang [15]. A cartography of environmental actions to deal with the interactions among those methods has been proposed. This cartography includes 46 environmental topics and defines the related action chains (121 actions) for covering these topics. A trace-back mechanism ensures the generation of the multiple eco-design options for treating the problems raised at a starting point (specific need concerning product design and environmental aspects).

The next example demonstrates how to use the environmental actions cartography for constructing multiple potential solutions for a critical problem: the recyclability of electric and electronic products.

Today, facing the stricter requirements from the WEEE directive and the needs from a model of recovery economy, the aspects of "recyclability" of an electric and electronic product became a crucial focus to be optimized. Meanwhile, several other stakeholders, such as the national collect platform, the recyclers and the final users, affect the final performances of the recyclability. A systemic planning within the particular operational contexts should be therefore considered to define the suitable working plan for a "Recyclability Optimization". So, the first step is to find out the most numbers of potential solutions, as more as possible to treat this problem.

Figure 1 presents an example about the different strategic options to answer to an objective of WEEE directive and the recovery economy model: "***optimization of***



Notes :

1. *In the frist left column, the list of 46 different environmental topics, 19 for EMS and 27 for eco-design.*
2. *The arrows, which string together the actions in a same line, present the process of working flow to resolve the topic.*
3. *The arrows link across the actions from different lines present the "interactions".*
4. *The gray arrows represent the parallel possible inputs from other topics and could totally replace the black one.*

Fig. 1 Explorative tracing the trajectory for eco-design objective: "Optimization of the recyclability of a product" (extract of [15])

the recyclability of a product". The process to explore the solutions will be described as follow:

Facing this objective (rounded in red in the first column of Fig. 1), the last action in the same line, "Calculation of improved product's recyclability", is the last targeted action to be performed (Fig. 1—by orange line—the last action in same line with an orange star). This initial objective is achieved once this action has been performed. Then the user of the method needs to identify the previous actions that could drive this final action. If there are multi-parallel previous actions, it means that there are multi-possible ways for resolving this objective (three examples presented by red, blue and green line). All previous actions are registered to describe the different branches (eco-design strategic options). And then, for each branch, by tracing back iteratively the previous actions of these new funds until the initial one which does not have any previous. The footprint of this exploration ensures the construction of a complete trajectory, from the first action to the last one. This constitutes the working process of an eco-design option initial objective.

In this example searching the process for "the optimization of the recyclability of a product", 21 different eco-design options within three scenarios have been defined (Fig. 2). The first scenario (the example tracked in red in Fig. 1) describes the classic option by using the "design for recyclability" method. This option requires the designer to redesign the product depending on some related criteria. The second scenario (the example tracked in blue in Fig. 1) provides a different strategic option, which requires the suppliers to demonstrate the new feature of recyclability of the product's components. Then the company launches an eco-design project to set up the evaluative criteria, and then, summaries all results to draw up the recyclability of the whole product. In this case, the collaborative activities (such as the evaluation, the annual review, and the cooperation) with suppliers are required to be set up and integrated into the corporate activities. Lastly, the third scenario (tracked in green in Fig. 1) describes a situation of collaboration between designers and recyclers. In this case, the designer improves the product either by focusing on the real operation of recycling, or by harmonizing and updating the recycling treatment process. An additional action can be taken at a corporate level, even if all real

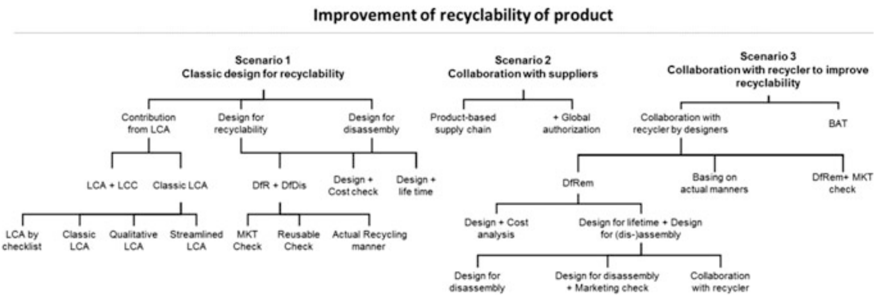


Fig. 2 Trajectories map for eco-design objective: improvement of recyclability of product, from [15]

activities are normally out of the corporate scope. The company can sign a specific contract with suppliers to optimize the “taking back” system for its product.

In this model, each branch shows an independent eco-design option (action process). Each of these branches can replace another branch. The redundancy of the branches ensures the robustness for treating this specific problem: “the recyclability improvement of electric and electronic devices” required by the WEEE directive, as well as the new recovery economy models. For example, if the company selects a trajectory (e.g. “collaboration with suppliers” in this example) this redundant design can quickly allow performing a variety of other possible backup options to fulfill the final objective in urgent cases, such as considering the lack of suitable suppliers. So the multiple possible data connection pipes (the interactions among different actions) and multiple contributions of trajectory enhance the robustness about the fault-tolerant ability of the program implementation [10]. It is necessary to mention that the above “applicable scenarios map” provides several possible trajectories, and these trajectories are not strictly independent. It means that the possibility of regrouping the different trajectories provides a great flexibility to plan an adapted corporate program to the company.

Thirdly, these above explored options are not only the general dashboard of the trajectories. In fact, behind each action described through the cartography, sets of operational resources, tools and recommendations are also proposed. These information can support the company to easily evaluate the operability of each trajectory and to integrate the selected trajectory into the corporate process. Such as, due to the WEEE directive, the waste of EE devices were treated by several recyclers. But the detailed data about the collection and the treatment of its product are unavailable for the company. So in order to optimize the recyclability of EE devices, the cartography recommends some scientific researches and case studies [3, 9]. This action seeks to guide the collaborations of the designers with these recyclers.

3 Harmonization of Eco-design Embodiments with Other Corporate Strategies Constructs the Sustainability Both for Ecological and Economic Aspects

As mentioned earlier, Eco-design is not a simple matter, especially in the sector of electronics and electric products, where it is part of a system considering quality, cost, security (etc.) as well as sustainability. The multiple stakeholders involved in the supply chain should be considered together to achieve the objective of eco-designing products and services. From above exploration in Fig. 1, the different eco-design strategic options require different stakeholders’ integrations. The scenario 1 requires the auto-analysis from the product designer. The scenario 2 needs a depth involvement from purchasing departments. The scenario 3 requires some collaboration between designer and recycler. It is therefore necessary to define the responsibilities and the working flow of all stakeholders. However, and seriously, the behaviours of these stakeholders will be constrained by their own professional strategy and related rules, as well as influenced by their own working flows and competences. So new added eco-design requirements cannot be contrary to the original strategy. Otherwise, the execution will be subjected to some great resistance. An example from the purchasing domain can be considered. For a start-up company, if the purchasing strategy is to construct the supplier network within the augmentation of supplier number, a strict supplier control and the remanufacturing options are not a smart option to be taken. The success of remanufacturing would indeed significantly reduce the volume of purchasing. This effect would lead to a risk of creating relationship troubles with the main supplier.

But inversely, if the tendency of eco-design is compatible with other corporate strategies, a suitable eco-design program can cooperate with each other to provide a systemic support of value creation [2, 4, 5, 8]. Meanwhile, the success of the eco-design depends on the capacities of all stakeholders. It means that even if an eco-design option was successful for a company, it would not absolutely be the case for others. Supplier control is a very simple options about the eco-design programming. But the precondition is that it exist sufficient numbers of suppliers that have the capacity and the motivation to make the co- design by themselves. If we count the cost to train the suppliers and the waste about the ineffective communication, this simple option is not feasible.

So, at the beginning of the strategic consideration, serious consideration about the compatibility between the potential strategic options and the global corporate tendency is an important condition for the success of any eco-design program to design electric and electronic devices.

4 A Decisional Framework to Optimize the Process of Eco-design Products

From the Sect. 3, this paper illustrated that the eco-design activities need to be compatible with other corporate strategies. An ideal eco-design strategy can cooperates with other strategies to provide a systemic solution to make the achievement of both economic and environmental aspects together. In order to analyze this compatibility, it is necessary to explore the different potential solutions within the different technical and operational structures. Section 2 demonstrated that based on a depth analysis, a cartography of environmental actions allows the company to finding out the various numbers of solutions for reaching a critical eco-design objective. The different definitions about the technical topics, the responsibilities of stakeholders, and the operational flows provide the data to analyze the compatibility and the possibility of cooperation. The next Fig. 3 illustrates a framework to support the eco-design program.

This framework defines a general process to harmonize the new eco-design options with other corporate strategies. This framework includes 4 different

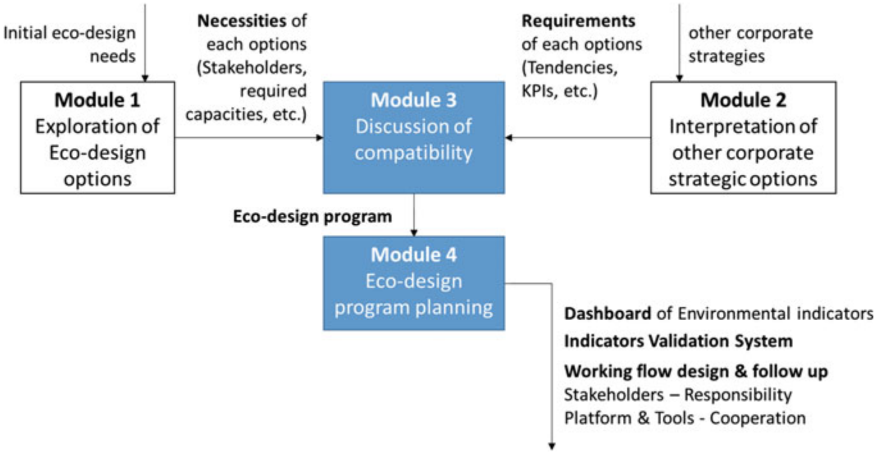


Fig. 3 Proposed framework for a systemic eco-design program

modules: the first module explores all possible strategic options of eco-design. The cartography of environmental actions is considered as a database to support this exploration. Within this database, the company could easily translate the eco-design objectives into some different series of eco-design actions and related definitions about required capacities, and responsibilities of stakeholders, as well as the related working flow. The second module is created to translate the principal corporate strategies into sets of key elements or indicators (KPIs). This translation aims to simplify the discussion and allows the comparison with the new eco-design options.

Within these two inputs, the third module focuses on the options compatibilities. In general, the corporate environmental managers might consider some following criteria:

The computability with the corporate strategic definition of environment: today, for the environmental issues, each company has its private definition. According to [13] four different types of strategic definitions about environmental issues have been defined. Some companies consider environment as a barrier for their business development. So there are a few budgets or supports to launch eco-design practices. Facing this definition, the simplest or cheapest eco-design strategic options need to be prioritized. However some other companies consider the environmental issue as a new opportunity for their technical innovation. So they wish to develop some new competences to take some advantage out of it. Facing these needs, the different options should be selected and highlight the ones that would bring some key technologies or which could produce the suitable results.

The compatibility with the KPIs of other strategies: if the new eco-design actions can be aligned to other corporate strategies, the company can significantly reduce the operational cost and the risks associated to those actions. For instance the marketing team could be pushing projects dealing with modular ways of selling the products and their services. In this case the "design for upgradability" method could be considered as a better solution for addressing the product end of life instead of "design for recycling" methods. Meanwhile, if the company is re-auditing suppliers, the new requirements about the sustainable supplier could be embedded into this project. And the results of this embedment could directly support the achievement of the related eco-design strategy.

The compatibility with previous environmental plans: due to the relationship between different eco-design options, sometimes, the results of previous eco-design data may be inherited by the next need. This inheritance can directly reduce the operational cost and risks. The eco-label exemplifies this situation: company "A" wants to be certified in type I eco label (ISO 14024) to communicate on the environmental results of its products. However, due to the limited of categories of covered products by the standard this company cannot find out any suitable label system in France (i.e. its products could only covered by a foreign label system). With the support of environmental cartography, the company finds out that some type III eco label (ISO 14025) would fulfill its needs. Meanwhile, some simplified LCA have been released by its designers. Therefore, by proceeding to the type III eco labelling the company just has to modify its Product Category Rule (PRC) in order to answer the needs of labelling system.

The compatibility with parallel eco-design programs: sometimes, there are multiple eco-design programs launched together in company. Some come from corporate level, while others would come from project level. The manager in charge of making the eco-design plan (either on corporate level or project level) therefore needs to consider the compatibilities of these programs. Basically, due to the relationship between the eco-design options, the common actions for multiple objectives can simplify the operational cost and encourage the motivation of stakeholders.

Once the suitable eco-design options have been selected. The last module (number 4) is to create support for the company to define the working process and the responsibilities of each stakeholders. The dashboard with sets of KPIs system, the methods of validation system, and the collaborative platform need to be carefully designed.

This framework and the related cartography of environmental actions had been tested into a French SME to define a suitable eco-design program. This company is an **electric and electronic company** producing lighting decorations for festivals. The company objective at the beginning was to "optimize the recyclability rate of its product" for being WEEE directive compliant. With the support of the cartography, a holistic scenarios map has been proposed to deal with this consideration. Similar with the above example (shown in Fig. 1), there principal scenarios were proposed: 1—Design for recyclability, 2—Collaboration with recycler and 3—Collaboration with suppliers. Other branches, such as the "design for disassembly", "design for upgradability" and "design for remanufacturing" have been also proposed to complete the solutions.

Based on these potential solutions, a set of discussions has been organized with the CEO, the purchasing manager, and R&D managers. The objective of these discussion is to define a suitable eco-design program by considering the compatibilities of these solutions with other current corporate strategies.

Firstly, Due to the lack of necessary internal environmental competences and knowledge, the company preferred the simplest solutions. But due to the lack of available suppliers (most of its suppliers were Asian SME), which had enough knowledge about recyclability improvement, the collaboration with suppliers was not cheap enough. So by initially referring to this preference, the classic “design for recyclability” have been selected and several other solutions, such as the “implementation of the remanufacturing process” were out of scope.

But facing the current corporate strategies, especially the strategy to reduce the volume of purchasing goods from Asian suppliers, and the corporate program to reduce the cost, the planer found out that the “remanufacturing” for its product could directly produce some potential benefits for these two projects. The lighting product and related component had a life stage of 10 years. However these products were only used for 1 year. If these products could be well collected, a major part of the waste could be avoided by remanufacturing the remaining unbroken parts. The recycled product could reduce the volume of purchasing which would indirectly reduce the purchasing cost. So by performing some preliminary benefits calculation, this company decided to make the “remanufacturing” strategy as a long-term tendency of corporate business.

So, within this new context, the actual eco-design initial plan needed to be changed in order to address the new objectives and to consider them as the short-term steps for simplifying the realization of the long-term tendency: remanufacturing. By considering its product profiles (the life time and actual business model allowing the possibilities for tracing and reusing the decorative lighting products and its supports), **the “design for disassembly” and “design for lifetime”, replaced the “design for recyclability rate”**. This action plan were therefore selected as the common solution to answer both the short term and long term objective.

The results of this case study demonstrated that the consideration of the compatibilities between the eco-design options and other corporate strategies can support the company to find out a more suitable eco-design solution. In this case, firstly, due to the initial preference, the remanufacturing option was out of the scope. But within the consideration of the relationship with other corporate needs, the company redefined a new innovative objective which was never been considered in their mind, and finally remanufacturing has been selected by corporates.

5 Conclusion

Today industries from the electric and electronic sector are facing the challenge of improving the environmental performance of the product (eco-design). Various corporate attitudes and their related policies conduct industries to launch different solutions of eco-design. In addition important amount of eco-design methods are available. The challenge of planning which eco-design method to use for a specific need is thus considerably increasing over time.

This research therefore aimed at providing a mechanism to generate suitable eco-design options or a set of methods for answering to the specific corporate orientations.

The existing eco-design methods used in the electric-electronic sector have been carefully analyzed and various 'interactions' between the actions followed in those methods have been identified. From this analysis, this research now provides a new network of eco-design actions for company, allowing them to explore different solutions and helping them to elaborate roadmaps for reaching some concrete eco-design requirements.

The results from this research have highlighted that the harmonization with the eco-design options and other corporate strategies is a key element to make decisions. The company is equipped to select the best solutions depending on its specified strategic constraints, as well as the whole dynamic operational context, and of each solutions taken in this context. This research illustrated a framework to guide the company in the consideration of these different eco-design options within its special context. Four compatibilities with other corporate activities have been highlighted. Within this framework and the proposed environmental cartography [15], a case study in a SME demonstrated that this method therefore efficiently supports the company in reaching eco-design goals.

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Part II
Energy System and Planning

Renewable Energy, an Essential Element in India's Energy Security (Electricity)

C.M.A. Nayar

Abstract Energy Security (both electricity and hydrocarbon) will be a major element in India's march towards prosperity and in that process, claiming her rightful place in an emerging multi polar world. India has to adopt sound principles of sustainable development in her own interest with a judicious mix for power generation with conventional thermal power and renewable energy. India, a nation blessed with natural resources and intellectual assets should have a strategy of its own for her development through creation of wealth in the Rural India and drawing strength from her domestic market. India has to fix a target for per capita consumption of electricity taking into account her growth trajectory as well as for ensuring that all citizens in the whole cross section of Indian society will be able to have a decent life-style. I fix this per capita at 3000 units per year in 2040 based on a bench mark study taking into account India's needs.

Keywords Energy-security · Renewable energy · Energy-neutral/energy+ buildings · Life cycle cost · Recycling of CO_2 · Hydricity

1 Introduction

India's economic progress with equity will depend largely on its capacity to ensure energy security (electricity). i.e., adequate supply of electricity at affordable prices to the entire cross section of the society. Any meaningful discussion on this subject is possible only if we accept the fact that India needs a judicious mix of different sources for power generation. It will be necessary to define this judicious mix in a short term, medium term and long term scenario bearing in mind India's requirement for fulfilling its vision of development, India's possibilities and the focus for sustainable development.

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2 Power Generation Scenario in India

Total Installed Capacity in 2014	250,256 MW
Of which renewable based capacity	72,490 MW (40,798 MW hydro and 31,692 non-hydro)
Generation billion kWh (2012)	1127 (11.4% hydro and 4.5% non-hydro renewable)

The share of renewable sources was 29% for installed capacity and 15.9% for electricity generation. India has announced plans for adding 175,000 MW of installed capacity from renewable sources by 2030 (100,000 MW of solar and 75,000 form other renewable sources). India has also committed during the Paris meeting of UNFCCC 2015 that the installed capacity from renewable sources will be 40% of the total installed capacity.

The average per capita consumption in India was around 940 kWh per year in 2012 against the world average of around 3500 kWh (around 7000 kWh in France, 12,300 kWh in USA and 4300 in China). India has to set a target of a per capita consumption of around 3000 kWh as a first step and 7000 as a second step. A per capita consumption of 3000 kWh in 2040 will correspond to a generation of around 4000 billion units. India has committed to have 40% of the installed capacity from renewable sources in 2030 and this could represent around 15% of the total generation and will correspond to 600 billion kWh when India achieves a per capita consumption of 3000 kWh.

3 A Judicious Mix for Installed Capacity

An ideal mix of installed capacity should correspond to 30% from fossil fuel and 30% from nuclear and 40% from renewable sources. Around 15% of the electricity generation will be from renewable sources and the rest almost equally divided between fossil fuel and nuclear. However, India has almost sealed the fate of nuclear energy by passing the Nuclear liability act making suppliers of equipment also liable for the collateral damages. No responsible supplier (foreign or domestic) will accept such a clause and hence I do not expect nuclear energy to contribute more than 10% of the total generation in the foreseeable future (it was around 3% in 2012). This would also mean that fossil fuel will contribute more than 75% of the total electricity generated in India for another two or three decades. CO_2 emission from fossil fuel based power plants is a very important aspect to be considered. India has made a commitment to UNFCCC that India will bring down the carbon intensity (CO_2 emission in metric tonnes divided by GDP in million $) by 33–35% by 2030 in comparison to 2005. However, India's CO_2 emission will go up considerably during this period. I expect the global CO_2 emission in 2030 to be around 60 billion tonnes (around 34 billion tonnes in 2014). In my view, the only way to contain the CO_2 concentration in the atmosphere will be to recycle CO_2 in the atmosphere and at source of production as well as the CO_2 in the oceans. A technology breakthrough is a must for achieving this objective.

4 Renewable Energy (Electricity)

There are several definitions for renewable energy and I would like to take the following definition for the purpose of this discussion.

> Any energy resource that is naturally regenerated over a short time scale and derived directly from the sun (such as thermal, photochemical, and photoelectric), indirectly from the sun (such as wind, hydropower, and photosynthetic, biomass), or from other natural movements and mechanisms of the environment (such as geothermal and tidal energy).

Major renewable sources in India will be Hydro, Solar, Wind and Biomass. Hydro electric energy is the single major source of renewable energy which has been exploited since long and the adoption of other forms of renewable energy has been recent. The following figures give the status as in 2012 (reference World bank data. US EIA data).

	World	India
Total Electricity generation Billion Units	22,700	1127
Hydro energy Billion units (% of total)	3769 (16.6)	129 (11.4)
Other renewable energy Billion units (% of total)	1519 (6.6)	51 (4.5)

5 The Right Place for Renewable Energy

The discussion will remain positive if we try to establish the right place for power generation from renewable sources without trying to denigrate other forms power generation. Unfortunately, the whole debate in India is highly polarized and this distorts the real issue. While it is the right of any citizen or group of citizens to oppose or support any form of power generation based on his/her conviction, the merits of renewable energy should not be mixed up with such partisan discussions. In my view, renewable energy has its place and the efforts should be to find this place with the available technologies and expected technological evolutions in the foreseeable future. This has to be done with public support. Cost of production and continuous availability of energy are important matters which could stand in the way of public support and we have to find innovative solutions in a pragmatic way.

6 Comparison of Cost of Production for Electricity from Different Sources?

The notion of "life cycle cost" is becoming increasingly popular and this should become the standard practice for calculation of the cost of electricity for accounting purposes as well as for comparison purposes. Life cycle cost would include the cost of managing a product from "cradle to grave" i.e., cost of acquisition, cost of operation, cost of managing the end of life including decommissioning, disposal and decontamination of the site. Recovery of value from the decommissioned product should be undertaken in an environment-friendly manner. Any meaningful comparison of cost of production of electricity from different sources will be possible only on the basis of life cycle cost. However, I must say that I do not find such an approach in India so far and this could be true in several other countries as well. I hope it will change and selling price of electricity will correspond to the real life cycle cost. While it is normal for the Govt to offer capital subsidy, higher depreciation limits and tax concessions for promoting new technology, it will be a wrong step to provide subsidy for the selling price of any product including electricity.

7 Importance of Renewable Energy in Rural India

In my view, India has to target the contribution of agriculture at a level of at least 15% of the GDP in 2030 (17% in 2010). This means that the growth in agriculture will have to be the same or more in comparison to the overall growth of GDP. This would also mean that India should not follow the growth model of some of the developed countries giving greater emphasis on urbanization ignoring agriculture. The definition of agriculture in the calculation of GDP includes, cultivation of crops, forestry, fishing and livestock farms.

It is possible to project India's GDP in 2040 as 27 Trillion $ based on certain assumptions of growth and the contribution by Agriculture should be around 4 Trillion $, i.e., more than twice the total GDP of India in 2011. The value addition to these agricultural products will have to take place within the vicinity of farms (preferably through cooperatives) and the industrial output on account of this value addition should also be around another 4 Trillion $ making a total of 8 Trillion $. All the services associated with these activities as well as the activities for the overall development of the villages should be around 6 Trillion $. This would mean that the rural India will contribute around 50% of the total GDP of. In other words, 70% of Indian households living in the Rural India will contribute to around 50% of the total GDP of India ensuring a reasonably good pattern for creation and distribution of wealth.

8 What Should We Do for Making It Happen?

The key elements will be energy (electricity & hydrocarbons) and water. Needless to say that basic infrastructures for education, transport, health care and communication are vital for any development. Even after 65 years as a Republic, 15% of the Indian villages do not have electricity at all (12th Plan report). Even a large number of the "so called" electrified villages do not provide electricity to a large majority of the people in the villages. In such a scenario, it is impossible to imagine that the Govt will be able to provide adequate quantity of electricity from the Grid to these villages in the next twenty or thirty years. The only way in which electricity could be provided to these villages will be through renewable energy sources and off-grid distributed power supplies. The actions of the Solar Mission of the Ministry of Renewable energy are in the right direction and it is necessary to activate all the possible avenues of power generation from renewable energy sources; biomass, geothermal, syngas, bio-fuel, mini hydro, wind turbines, solar etc. The full potential should be achieved by 2040 in a step by step manner. Biomass facilities should make use of all the bio waste including excrements from the animals and even human beings. The electricity requirement in the villages will be for household consumption, industrial use for Small and Medium scale industries (including cold storage) and commercial use as well as for common facilities for the community. In fact, Small and Medium Scale Industries should become the backbone of India's development similar to what is happening in Germany. While the solar panels should provide the energy during day time, power generation from bio fuels, biomass and syngas and pumped storage system should provide energy during night time.

9 What Can Be a Probable Scenario?

The total energy consumption for house hold purposes of 240 million families in 2040 could be estimated to be around 720 billion units (240 million $\times$ 3000 units) with a distribution of 60% for the 160 million rural house holds (2600 units per household) and the remaining 40% for the 80 million urban households (3600 units per household). In my view, the entire requirement for the household consumption in the rural India should come from renewable energy source, meaning 430 billion units. This should be through a combination biomass, solar, wind, syngas, hydro (including pumped storage). It will also be necessary to explore the possibility of using solar concentrators for adopting "Hydricity (hydrogen + electricity)" using the latest developments in technology.

The manner in which India handles the demands of urban Indian household should be different. All the new houses and flats should be compelled to have solar panel installations from 2020. In view of the lack of space, it may not be workable to mount enough number of solar panels for making the urban houses energy neutral. I would, therefore, propose that 50% of the requirement of the urban households should be met from renewable sources. All the surface level car parks should be compelled to have solar panels on the roof. Cities should also be equipped with "Syngas" based power plants using carbon-based waste generated by households. The total electricity generated in this manner in the urban area should correspond to around 170 billion units. In this scenario, India will have 600 billion units (430 + 170) from renewable energies for household use. It is also my view that all the industrial and commercial buildings built after 2020 should be energy neutral for their requirement of electricity for lighting, heating and air-conditioning. The requirement for industrial purposes should continue to be from conventional thermal power plants.

Recently, there has been an integrated approach to solve the problems of housing in Rural India along with the basic amenities of electricity, gas, water and sanitation and I am attaching the details of a 55 square metre energy neutral home designed and developed by a well known architect in Kerala Mr. N. Mahesh. The waste including the toilet waste is used for producing biogas for use in the house. The electricity is generated by a 500 kW solar panel system with battery and produces around 65 kWh per month for use in the house. The walls are made of bricks made from fly ash from coal based boilers. The roof is made of ferrocement sheets. The estimated cost is around Rs. 5,50,000 (around 7500 Euro). It will be possible to add additional solar panels for pumping water if required. It will also be possible to mount a solar water heater on the roof top.

10 Legal Framework for Promoting Renewable Energy

I would propose the following:

The Govt should pass a law for making "energy neutral" or "energy +" buildings an obligation from 2020 onwards similar to the EU Directive on the subject. All the new buildings (residential, commercial or factory) with a floor area of more than 200 square metres should have an obligation to have energy neutral design. The grid should be suitably modified for having bidirectional flow of current. The consumer should be able to pump in the additional quantities generated during day time to the grid and draw the energy from the grid in the night. The Govt may decide to give a capital subsidy for a pre determined period of 5 years for promoting such investment. Energy + buildings should be given an additional capital subsidy. Surplus electricity generated from renewable sources should be bought by the Grid at the ruling rate for peaking requirement. The business plan for any industrial activity or commercial activity should provide for such capital investment and work out the ROI based on the total investment and depreciation of up to 25% on the investment for renewable energy. A further incentive may be given as income tax concession for the total renewable energy produced by the company.

The international airport in Kochi, Kerala has commissioned a 12 MW solar power plant in August 2015 for meeting the total requirement of electricity of the airport and thus making it the first airport in India (perhaps in the world) to be energy neutral for electricity (photo attached).

11 Conclusion

(a) Energy Security (both electricity and hydrocarbon) will be a major element in India's march towards prosperity and in that process, claiming her rightful place in an emerging multi polar world. India has to adopt sound principles of sustainable development in her own interest. India, a nation blessed with natural resources and intellectual assets should have a strategy of its own for her development through creation of wealth in the Rural India and drawing strength from her domestic market.

(b) India has to fix a target for per capita consumption of electricity taking into account her growth trajectory as well as for ensuring that all citizens in the whole cross section of Indian society will be able to have a decent life-style. I fix this per capita at 3000 units per year in 2040 based on a bench mark study taking into account India's needs.

(c) India's growth trajectory will have to take the whole Rural India in the fold. Rural India should be capable of contributing 50% of the GDP in 2040 and should enjoy the fruits of prosperity. India is, today, the biggest producer of fruits, milk and vegetables and the second biggest producer of wheat and rice in the world. The output of these products will multiply by 10 by 2040 and Indian citizens should have the purchasing power to consume these products in a society where no one will have the problems of malnutrition.

(d) It is in this background, I have tried to define the importance of Renewable energy and its possibilities as well as its limitations. It is my assessment that the full exploitation of renewable energy will help India to meet the total requirement of electricity in the rural house holds estimated to be at 430 billion units in 2040 with a judicious mix of all forms of renewable energy (electricity); solar, wind, small hydro, biomass, bio fuel and pumped storage.

(e) McKinsey estimates that India will be awfully short of water by 2030 with supplies only at around 70% of the demand. Solar energy could provide pragmatic solutions for desalination of sea water through the classical "reverse osmosis process" or through the "Humidification and dehumidification process".

(f) India has to take the lead for a global research for recycling CO_2 and for production of hydrogen as a fuel to replace hydrocarbon in an economically viable manner.

Making Compatible Energy Planning with Urban Decision-Making: Socio-Energy Nodes and Local Configuration

Gilles Debizet and Antoine Tabourdeau

Abstract This communication will develop a specific concept, the socio-energy node (SEN), to help understand energy assemblages in urban spaces. The SEN concept broadens the scope of planning to urban-energy interaction, the better to understand two main points. First, it informs questions about how to upgrade large energy networks and hybridize them with self-sufficient energy loops. Second, it aims to provide support for energy planners when modelling multi-actor energy systems. We therefore emphasize the importance of qualifying relationships between energy and urban-planning stakeholders and propose a method for implementing—and reconsidering—energy planning in cities, by breaking energy systems down into SENs and by studying how they "plug" together and into local configuration.

Keywords Energy planning · Stakeholders · Renewable energies · Socio-technical regimes · District

1 Introduction

In France, the eco-district concept has gained popularity in the last 15 years as a sustainable concept for implementing low-carbon and renewable energy standards in urban planning. The notion widens the range of technologies for decision-makers and is required for construction stakeholders to combine their skills with these new technologies.

Energy transition has largely been scrutinized from a technological or sectoral perspective: the technological perspective focuses on the engineering and economic

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performance of renewable energies and low carbon technologies, through technical and econometric models, and somehow neglects the socio-technical dimension of urban approaches. This "technological fix" [1] leads to viewing stakeholders as one of the main "barriers" for the deployment of technologies [2] in a determinist approach. Over the last three decades, Science and Technology Studies (STS) have underlined the "social construction of technology" and developed arguments towards a pragmatic posture, including the co-evolution of organizational forms and technologies [1]. Applied to the urban context, the co-shaping of cities and energy has been underlined, especially through a special issue of *Urban Studies* [3]. This paradigmatic shift in the understanding of innovation led authors to develop intermediary objects to underline a "missing organizational context" [4], characterized by problems of mis-alignment between scales of socio-technical systems and government, regulation, productions of norms, experiments, etc.

Based on the Socio-Energy Node (SEN), this communication investigates the conditions in which energy technologies were integrated in eco-districts, we substantiate different geographic configurations for sustainable urban energy and, therefore, for urban energy networks. This paper concludes with propositions regarding the compatibility of energy planning with urban development and its stakeholders.

2 Definition of a SEN

District heating, solar panels on top of buildings, geothermal heat pumps or biomass heating inside buildings or small hydroelectric systems cannot be considered as a part of the incumbent energy networks since the energy sources and the decision-makers differ from the large historical technical systems [5]. For the same reason they usually cannot be considered as an extension of building energy systems either. Hence, we suggest to treat these elements as all or part of a Socio-Energy Node (SEN).

A SEN is a group of physical elements which collect, convert and/or supply energy and are built by the same decision-maker [6, 7] in interaction with other stakeholders and socio technical rules. District heating systems are not the only kind of SEN: internal building supply chains (electricity and heat indeed gas) are built by the same decision-maker (a real estate company), so they may be seen as two other SENs (one for electricity and one for heat). Both public and private networks can be considered as SENs too, connected to other SENs. Therefore, groups of SENs make up the energy system(s) of the city. It is important to underline that the SEN is distinct from innovation: within a SEN, there can be either no specific innovation or deep changes.

The SEN concept is based on socio-technical concepts like the Actor-Network Theory. The SEN is partly located within one or more energy-supply chains (energy flows) and it is a project led by a decision-maker interacting with human and non-human actants.

3 Theoretical Background in Energy and Urban Planning Literature

Energy transitions involve multiple innovations in energy and urban planning, as well as in economic and managerial studies. Perspectives such as the Multi-level Perspective [8] focus on innovation processes but somehow neglect the integration of socio-spatial processes [1, 5]. The increasing weight of decentralized renewable energies requires these processes to be reconsidered. The first concern is the link between technological systems—energy networks—and socio-political considerations, particularly with regard to energy transition. The second concern is the ties between energy and cities and the third between energy planning and business.

Technological networks play an economic and social but also cultural and ideological role [9]. Hence, large technological networks, as developed since the 19th century, have shaped urban governance. Energy infrastructure also engages the competencies and political choices of urban authorities. Changes towards more decentralized, polycentric governance models and their combination with "sustainable urban development" since the 1970s prompted Coutard and Rutherford to suggest the notion of "post-network" cities [5], engaged in new energy infrastructures, which entirely reconfigure urban operation. The SEN enables to grasp the reconfigurations of energy systems within a place, that is with an urban-planning input. Hence, the SEN opens the black box of urban politics with regard to climate change and energy transitions, making it possible to monitor changes in urban infrastructures.

Scientific works highlight the ties between urban and energy studies: as Jaglin [10] wrote "cities are increasingly recognized as critical arenas for addressing energy issues". This means that energy issues and urban planning are closely interlinked and cannot be understood separately. The concentrated urban energy production (which can be either injected in public networks, self-consumed or supplied) opens a wide range of options for energy management. The question was raised to distinguish which scales are more relevant to applying energy strategies [11]. This involves exploring unusual scales, especially intermediary between large technical network and energy end-users (and sometime producers). We would like to emphasize that the SEN is an operative tool enabling us to define the different human and non-human components interacting in energy planning processes. **Our first hypothesis is that the use of renewable energies in urban areas requires us to consider intermediary scales between buildings and large technical networks**.

Recent papers focus on heating demand and the key role of district heating systems for energy transition to more efficient and diversified energy systems [12–16]. With more stringent climate policies and the necessity to reduce energy consumption in existing building blocks, the research question has moved to the economic feasibility of district heating because of possible trade-offs between energy efficiency and fossil free district heating [17–19]. The second issue is electricity supply and particularly smart grids—ICT, smart meters, demand/response, storage, etc. [20, 21]. The other focus concerns electricity alone with still limited research on smart energy systems taking account of heat, electricity, cooling, gas, storage, energy efficiency [22–24]. Most of them concern the global (national) level or a specific project but some authors are clearly interested in the possibilities offered by smart energy systems for the supply of urban areas [25] or districts with near 100% renewable energy [26]. It therefore addresses the economic feasibility of an energy system but does not explore the social involvement and business models of each stakeholder. The diversity of resources and of geographical scales and also, the links to energy saving by consumers favour intermediaries: there could be new business models and/or new stakeholders. The business model concept enables to represent how organizations participate in such collective projects by proposing, creating and delivering value to the market. The value chain of business models is usually developed according to a horizontal coordination, usually implemented in sustainable innovation [27]. However this coordination requires agency [28, 29] which is not an equal role for the various stakeholders. Hence the main actors of a business model mobilize a value chain including other business models with their own agencies.

Our second hypothesis is that **the value chain of a business model for an urban energy system depends on other inter-connected business models**. Energy planning must consequently take account of value created by the various business models in the energy supply chain (and loops).

4 Material and Method

The climate change emergency requires rapid and local changes in energy supply. We have focused on energy innovations within eco-districts. The present work used eco-district case studies to identify changes in energy planning practices.

The eco-district idea gradually took shape at the end of the 20th century. The Aalborg Charter in 1994 was a turning point in its definition and recognition [30, 31]. The idea is widely used in French-language literature, especially since the French ministry of environment initiated the "EcoQuartier" award in 2009 [32]. The eco-district brings sustainable development principles into urban planning, by integrating energy efficiency, generation of renewable energies, ecological improvements, etc. Eco-district is a plastic term encompassing many practices and allowing us to question urban planning. In France the eco-district approach is used as a planning concept for districts delivering social and environmental standards, which otherwise face blockage by some stakeholders.

We conducted this analysis as part of the NEXUS project, funded by the French Energy and Environment Agency (ADEME).[1] The operational target was to design urban energy coordination scenarios for 2040, considering the development of renewable energies, especially the management of their intermittencies [6, 33, 34]. The diversity of actors requires a diversity of disciplines to include specific operational notions (business models, urban planning, energy policies, etc.).

Beforehand, a bibliographical survey was carried out, allowing us to identify about 12 European eco-districts presenting strong commitment to renewable energies [35]. We sampled a diversity of low-carbon technologies (biomass, photovoltaic, geothermic, CHP, sewage-water heat recovery, etc.) [36]. They concern heat and power grids [37].

Twenty interviews were conducted at the **De Bonne** eco-district (Grenoble): local authority representatives, town and energy planners, urban project managers, architects and energy consultants, local energy operators and, for four building projects, developers, architects, energy consultants and representatives of residents. De Bonne urban project includes 800 residential units, a shopping and leisure centre, school and several residential services for senior citizens, students and tourists. It received awards from the European Concerto programme in 2005 and the French Government in 2009 for its early energy performance and variety of energy resources, especially an innovative Combined Heat and Power (CHP) located inside buildings (Fig. 1).

Five interviews were carried out at each of three other eco-districts. In Fontaine and Nanterre, we interviewed municipality representatives and directors, energy consultants and/or the energy contractor, project manager and building developer. **Bastille** is an urban regeneration project located at Fontaine, a suburb of Grenoble. Several new social housing buildings, a refurbished condominium, new streets and district heating supplied by a wood-fired heating unit make up this project (Fig. 2). **Sainte-Geneviève** is a new development on a former industrial site located at Nanterre, a suburb of Paris. Six hundred residential units consisting of residential real estate and social housing are connected to a heating network supplied by a unit using wastewater and geothermal probes (Fig. 2).

The fourth case study was **Issy Grid**, a smart grid experiment led by several companies located in a district of Issy-le-Moulineaux, a suburb of Paris. The companies are working together to experiment with information and virtual flows between their office buildings ('virtual' as long as they themselves are not allowed to buy or sell power). The experiment includes PV panels, car battery storage connected to the electric grid of an office building (Fig. 3), and mitigation of

[1]This article mobilizes results of the research project « Ecoquartier NEXUS Energie » (Eco-district NEXUS energy), co- funded by ADEME (French Environment and Energy Management Agency), and led by the laboratory PACTE-CNRS (coordination Gilles DEBIZET), the federative research structure INNOVACS, the laboratory EDDEN (UPMF), the INES (CEA) and Grenoble Ecole de Management: http://www.nexus-energy.fr/.

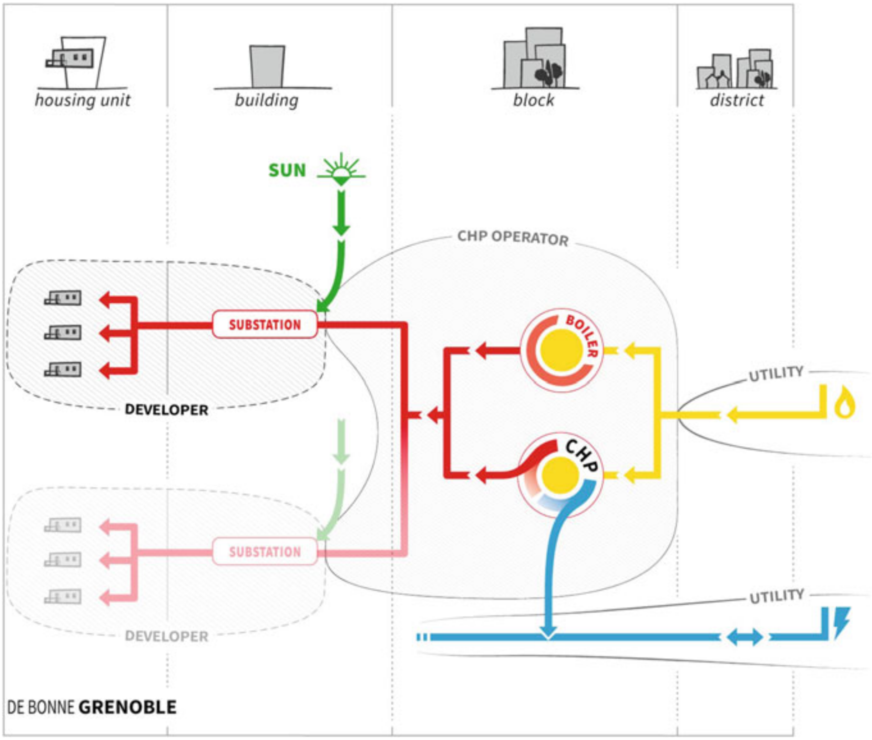

Fig. 1 SENs around a block-CHP SEN, De Bonne, Grenoble, France

consumption peaks by associating office and residential buildings. We interviewed the main stakeholders of this voluntary collaborative smart grid SEN.

5 Results: Innovative District-SEN as an Intermediary Between Usual and Renewable SENs

A determinist approach to planning such as the techno-economist posture described in our theory section (2) cannot successfully implement innovative urban solutions because it makes no allowance for the ability to produce different assemblages. How an unusual energy resource could be activated? Which organizations an energy-planner should take into account before technical and economic modelling?

The SEN concept highlights interaction between standards networks and stakeholders. The nature of such interaction differs, but each instance shapes energy planning. Through the intermediary approach [38] underline the need for intermediaries "between this triad of provider, regulator and user". The assemblage of SENs bridges not only physical networks like traditional large networks and

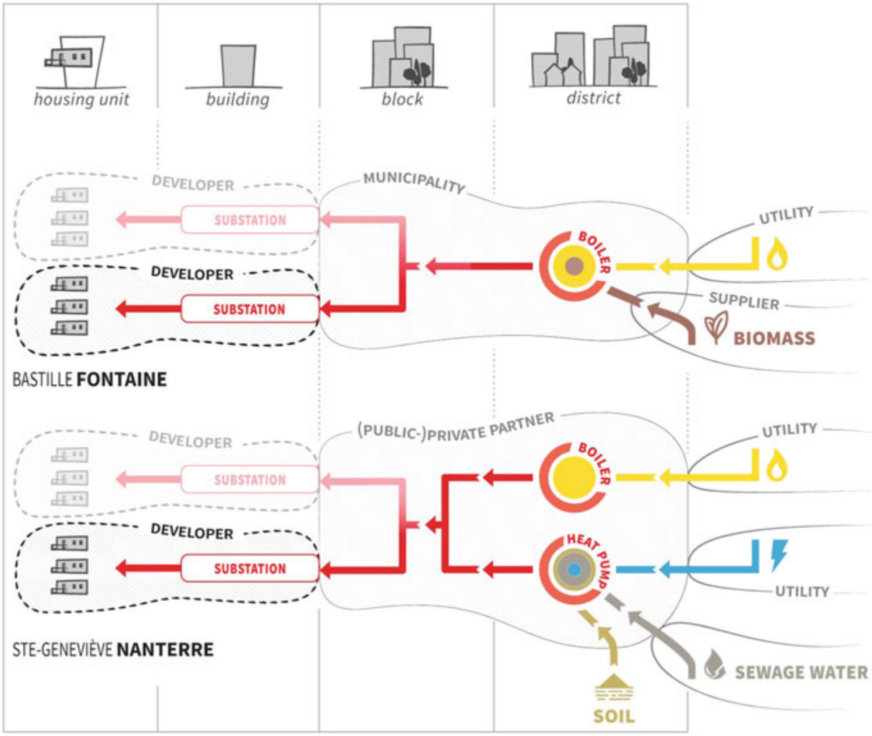

Fig. 2 SENs around a district heating SEN, Fontaine and Nanterre, France

'inside-building' networks, but also provides an outlook on these different types of interaction and how they are put together. We shall therefore propose several operational categories of connections around an intermediary SEN.

Our results underlined that four different types of SEN can be connected to an intermediary SEN, as shown in figure [4]: (1) large technical networks, (2) buildings and solar panels, (3) non-continuous supply chains, (4) waste and geothermal resources. Both are implemented in a specific local configuration: (5) city and communities. These five types have different governance modes, which specifically shape the intermediary SEN (centre of Fig. 4).

(1) Large technical networks convey energy to the intermediary SEN and, sometime, buildings, mainly from outside resources e.g. nuclear electricity, gas, and, to a lesser extent, from local resources, e.g. solar and solid waste incineration. These networks comply with specific energy standards and regulations usually defined at state level. Large technical network is a type of SEN.

(2) Buildings are places for consumption. In this configuration, developers and owners are the main decision-makers and conform to local urban regulations and buildings standards regarding connections to large technical systems. The developer usually builds the energy systems inside a building and rooftop solar panels.

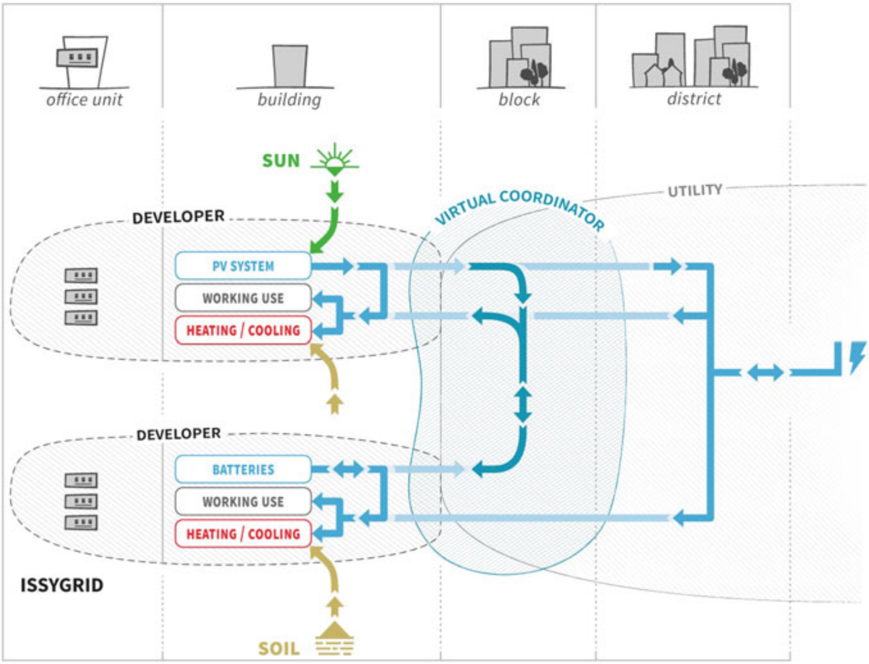

Fig. 3 A 'smart grid' virtual SEN added to usual power SENs, Issy, France

Hence, the intermediary SEN (centre Fig. 4) is connected to various SENs (inside buildings). Building with or without solar panels is a type of SEN.

(3) In non-continuous supply chains (woodfuel for instance), the resource is conveyed in its original form (wood) to its place of consumption and then converted into heat in a boiler. Intermediary SEN operator buy volumes of energy instead of power. There is no wood-energy sector as such in France [39], hence stakeholders belong to very different socio-political arenas and are not subject to powerful public regulation since the supply chain is non-continuous. Gas and fuel delivered by trucks encounters the same issues. A such supply chain could be considered as a SEN.

(4) Wastewater and geo-thermal heat recovery are usually located close to the intermediary SEN since conveying heat over long distances is expensive. Heat transfer is limited by the rated power capacity. Extracting heat from wastewater depends on the waste collection network. Geothermal rated power requires the approval of local/regional authorities, in line with state environmental standards and procedures. Such system could be a specific SEN or a part of the intermediary SEN (centre of Fig. 4).

(5) SENs interact with city and communities through economic and environmental effects. The use of local and renewable energies instead of fossil fuel (or remotely generated electricity) is a means of creating jobs and retaining wealth

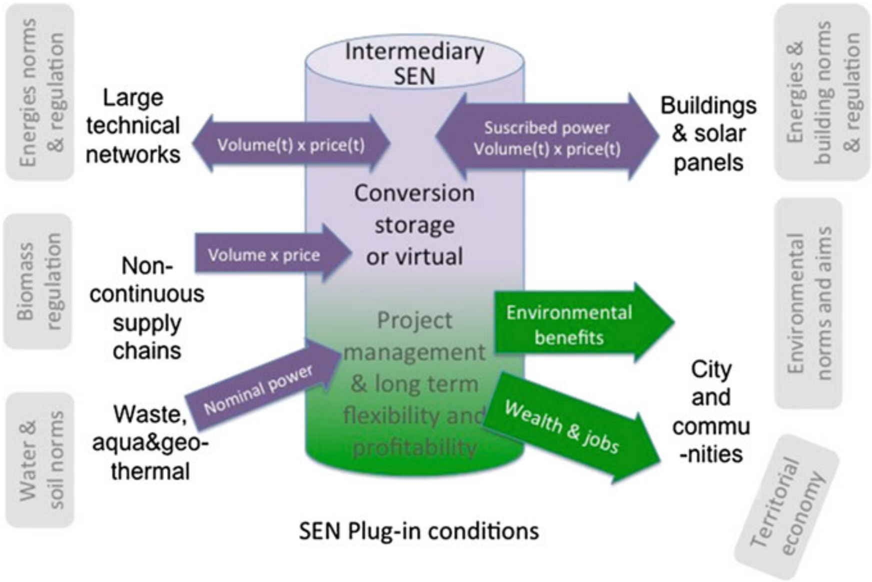

Fig. 4 SENs and local configuration around an intermediary SEN

locally, while preventing air pollution. Avoiding GHG emissions is also a way of demonstrating solidarity with the global community. The local authority usually approves (or not) the implementation the intermediary SEN and affects its design. City and communities shape a local configuration relative to the intermediary SEN.

By connecting these SENs and configuration, the intermediary SEN has both economic (labour, capital) value and environmental impacts (GHG and particle abatement). While SEN is usually part of energy supply chains, it interacts with a local configuration. The SEN notion may help planners to combine urban planning/project and energy generation from renewable sources, and therefore energy transition.

6 Conclusion: Reconciling Energy Planning with Urban Decision-Making

This paper proposes energy planning methods, drawing on the SEN concept. Neither the city nor its energy systems can be built according to a determinist top-down planning; Transformations of city and energy systems are—and have to be—actually aligned. This tendency is being reinforced by the massive development of decentralized renewable energies. A pragmatic posture is consequently needed.

Thanks to the SEN concept the various components involved in assemblages can be identified in two main ways: (1) the SEN concept identifies each energy system; (2) the SEN identifies the stakeholders and the rules, which both interact within a sustainable district energy project.

(1) The business model allows us to understand the point of view of decision-makers and project-leaders, who could apply economical methods based on return on investment: our results show the need to re-think these methods since organizations participate in an innovative SEN projects to gain rewards, which are not just economic. This study shows that local jobs and environmental issues are also driving sustainable intermediary SENs.
(2) Then it is necessary to integrate stakeholders and local artefacts interacting with the district-energy project decision-makers, in order to provide relevant potential energy resources and implement political, economic and territorial issues that shape together a specific local configuration. The four types of SEN are seldom all in interaction in the same district (more often two or three) but identifying which are interacting in a given intermediary SEN makes it possible to specify and integrate the project environment and constraints for planners.

We propose the SEN concept and identify four types of SEN that interact with a district energy system like district heating or smart grid. These types of SEN are mainly generic: each one is mainly shaped by the same technologies and, even less so, same organizations wherever the location. Therefore the rules of assemblage of an innovative intermediary SEN with the other SENs can be modelled. The multi-SEN model then have to be adapted to the local configuration. SEN could be a useful concept for energy planning in urban areas.

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A Tool to Optimize the Energy Flows in a Smart Building with Technic and Environmental Criteria

Vincent Debusschere, Léa Dodet and Céline Llamas

Resume A tool is currently being built that will allow to compare different control solutions of future Net Energy Buildings (also called Smart Buildings). The first step of this work, which is presented here, is to build an optimization tool and to validate it on various scenarios mainly based on technical criteria, but also being able to evaluate environmental impacts for the different components in a preliminary manner. The long term objective is to decide at one point in time whether to consume electricity from the grid or to use local productions means, like PV panels or energy storage, based on technic, economic and environmental criteria.

Keywords Optimization · Demand-side management · Flexibility assessement · Smart buildings · Environmental impacts

1 Introduction and Context

The environmental profile of products and services that meet our individual and societal needs is shaped by design activities. To achieve a more sustainable development, any system should deal more effectively with environmental issues in the design as well as any social and economic aspect that could come in addition to the pre-existing technical ones, as symbolized in Fig. 1a. But actually the integration of environmental objectives in the design process is still very confused. Although not yet fully embraced by the industry, the principle of life cycle of products is widely recognized as a useful framework designed to understand the links between the needs of society, economic systems and their consequences on the environment.

The life cycle of a product or a service includes all activities from extraction of raw materials, manufacturing and use to final disposal of any wastes, as remembered in Fig. 1b. It also encompasses assessing the impact of the use of energy and

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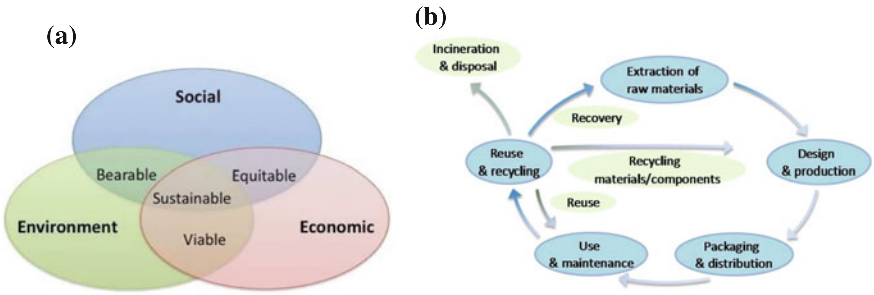

Fig. 1 Life cycle assessment and sustainable development. **a** The principle of sustainable development [1]. **b** The life cycle of any product or service [2]

materials on and from the environment, and of evaluating and implementing opportunities to contribute to a more sustainable development.

The energy consumption in housing is the object of many optimization studies, often taking into account storage and local production means. Regarding the objectives, these optimizations serve the consumers, network managers, etc. mostly based on profit maximization. Since profit is not often related to sustainable development, the aim of our study is to compare some optimizations (which come from classical scenarios and serve the inhabitants or the network managers in a Smart Grid context) based on the environmental impacts that they induce on a defined duration.

In a Smart Home, a main Energy Management System or Energy Box could be implemented to manage information about energy production, consumption and storage based on prices signals coming from the grid operator. It would process the information and give commands to the local control system related to every actor in the house, to accomplish goals like user comfort, energy efficiency, bill reduction or grid operator requests. In this context, we are building an optimal control algorithm able to coordinate a typical electrical architecture of a Smart House with technic, economic and environmental criteria in mind [3].

That optimizer module takes into account energy production, storage and energy pricing that enables the coordination of that typical houses' electrical architecture. Using data from a predictor module composed with meteorological forecasts, user behavior and houses' electricity consumption data from the G2ELab (Grenoble Electrical Engineering Laboratory), the optimizer should be able to generate midterm production, storage and consumption plans in compliance with technical restrictions.

Residential energy demand profiles are strictly related to people's lifestyle, so they present power peaks related to the building's occupancy. However, those power peaks are sometimes dangerous for the resiliency of the grid and costly for both grid and consumers. Many strategies have thus been developed in order to reduce those peaks. The strategies referred to as "advanced demand-side management" are then developed, aiming at controlling the elements of a building that are related to energy production and consumption.

All these advances are interesting for the grid operators, in order to increase the controllability of the power flows. But is there an environmental benefit of introducing more flexibility into households for that purpose compared to the use of the already existing grid architecture, which is able actually to provide the necessary power with a very low structural environmental and economic cost? The objective of the present work is to investigate this issue.

2 Framework of the Study

The considered system is presented Fig. 2a where all blocs (solar, storage and grid connection) are subject to assessment after optimizing the energy fluxes involved in an operation previously defined in various usage scenarios. These scenarios depend on the consumption power, the load profile, and other characteristics regarding for example the storage capacities and the presence (and size) of the grid connection.

An optimization block must generate mid-term production, storage and consumption plans minimizing different cost criteria and taking into account predicted information about future consumption, energy prices, local photovoltaic (PV) production, and technical restrictions related to the system architecture and non-linear behavior of some of its components.

The objective is to assess the environmental impacts of this system based on the integration of different components (especially the PV panels, the storage compared to a grid connection) in order to fulfill the useful service defined as “providing electricity to a household during five year”.

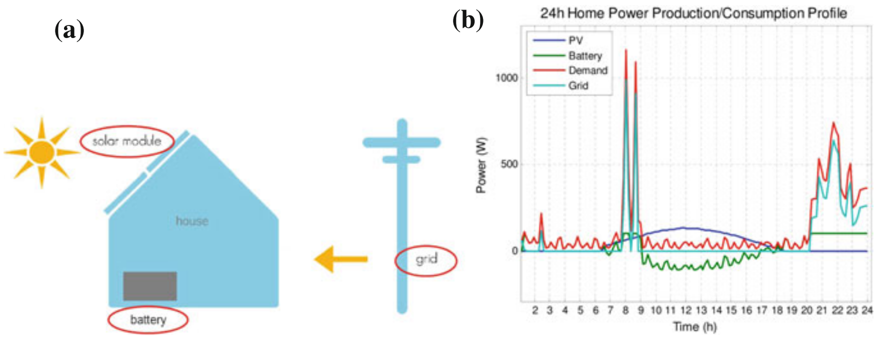

Fig. 2 The system and its optimization. **a** The considered system. **b** Optimized load curves as a support for the analysis

2.1 System Characterization

The hypotheses considered in the present study correspond to a typical residential consumption associated with potential local energy storage and energy consumption. These curves have been obtained partly after optimization and are partly based on actual measurements. Once we have the operation of this system, the need is to assess, depending on its location for example, what are the environmental costs associated with specific combinations of production and consumption means still able to cope with the electricity demand of the household (we do not consider that it is possible to act on the consumption profile yet).

Depending on the history and the characteristics of the electric grid, most environmental impacts could come from the consumption of energy from the grid, or from a solution improving the self-sufficiency of houses. The objective is to compare the contribution of the components, depending on their optimized use, in some of the major actual environmental impacts.

3 System Assessment

We considered the possibility to have a local production through PV panels [4], a local storage facility [5] and finally a possible grid connection [6].

3.1 Pv Panels

Even though no pollution is emitted during the transformation of solar energy into electric energy, the manufacturing, the operation and the processing at the end of life do have an environmental impact, like any other industrial product [7]. In PV panels technologies we can distinguish the following main families:

The silicon industry. Historically, this is the first series developed. Started in the 50s, it still offers, at present, one of the best compromises between efficiency and cost. Mono and polycrystalline silicon technologies are available in that industry.
The thin films industry. These technologies are based on materials with a high absorption coefficient of the solar spectrum to reduce the thickness of the layer of semiconductors.

Other promising technologies such as organic materials, nano-crystalline materials or structures multi-junction suggest excellent future performance and are now at the stage of research [8].

3.1.1 Impact on Landscape and Local Environment

Most systems are built on a building or an urban infrastructure. Those systems have no other direct impact on the local environment than the visual modification of the landscape. This alteration could be positive or negative, since the visual aspect is subjective.

Photovoltaic systems on the ground do have an impact on the landscape. Moreover, the installation of a PV farm on the ground has direct consequences on the local natural environment: hydraulic erosion, modification of the biotopes, etc. The main risk on the local ecosystem is the removal of wildlife when the field has to be railed in. In this case, the solution is the implementation of ecological corridors.

One of the fears concerning panels built on the ground is the competition with agriculture, but studies have shown that if solar panels equivalent to 10% of the total installed capacity in France in 2020 were built, the occupied surface would be around 2200 ha, which would only represent 0.0075% of the useful agricultural area. Moreover, panels could be built on uncultivated grounds. Hybrid installation could be also considered, mixing agricultural structures and energy production systems [9].

3.1.2 PV Systems Recycling

A photovoltaic system mainly consists in modules and inverters. The rest is made of classical components and electrical connections whose recycling is not specific. After separating the cables, junction boxes and wire ropes, the recycling of modules made of crystalline silicon can undergo thermal or chemical treatment. The recycled cells can then either be reused for the fabrication of new modules or melt for the fabrication of silicon ingots.

3.1.3 Manufacturing and Environmental Impacts

The measure of the environmental impact of a photovoltaic installation is carried out through a life cycle analysis of the system, from its fabrication to its installation, its operation and its end of life.

The manufacturing processes have several steps. We can cite for example the carbo-thermal reduction of silica in an electric arc furnace, the refining of silicon solar by a chlorine gas technique method, the crystallization of the silicon ingot and the cutting of the plates, the manufacture of solar cells by doping, polarization and anti-reflection treatment, the module assembly by encapsulation in glass, and finally the installation of the system including wiring and inverters.

The life cycle analysis goes from quartz mining to the production of electricity for 30 years, without a systems' end of life yet, and with some replacements (for example of the inverter).

Manufacturing reveals a silicon consumption from 10 to 15 g/Wp, toxic elements (Pb, Br, B, P), the use of metal with limited resources (Ag), and consequent energy expenditure due to aluminum and silicon (40%). It causes the generation of chlorinated wastes, of sludge containing silicon and gas and effluent from the use of chemicals.

The results of the analysis of the life cycle is that the energy is the major impact, with about 30,000 MJ of primary energy per kWp or 2500 kWh. To characterize the environmental effects of a photovoltaic system, relevant indicators are the energy payback time, which is about 3 years, and the greenhouse effect, which is about 70 g of CO_2 eq/kWh for France.

3.1.4 Energy Payback Time

An energy source could be considered "renewable" when it produces more than what it needs during its life cycle. The "energy payback time" is the ratio between the total consumed energy during the fabrication, the transport, the installation and the recycling, and the energy produced each year. A study conducted in the PVS program of the IEA (International Energy Agency) shows that the energy payback time of photovoltaic systems is very good and varies between 1.36 and 4.7 years, depending on the country and the type of integration (roof or front) [10].

3.2 The Batteries

Life time of batteries strongly depends on the use conditions and the number of charge/discharge cycles. In order to last the battery life up to 10–15 years its State Of Charge (SOC) has to be kept above 50%. The three following parameters are the most influent for battery life time:

- Resistance to high temperatures,
- Sulphation of lead plates,
- Manufacturing defects and under-sizing.

Batteries are composed of heavy metals which are toxic and can be very harmful for the environment. Some of these materials are non-renewable at human scale. Therefore, recycling is the main concern when talking about environmental impact of batteries.

The European rule 2006/66/CE sets that at least 65% of the average weight of the battery has to be recycled. Also, putting it into landfill has been strictly forbidden. In France the collect of batteries is organized according to the extended producer responsibility since 2001 for private households and since 2009 for industrials. There are two organisms which are responsible for batteries collection: COREPILE and SCRELEC. Collection of lead-acid batteries has been self–financed in France for some years because lead is a very valuable product. Used lead-acid batteries have to be considered as dangerous waste during transportation.

3.3 The Household

We want to compare the environmental impacts of three optimization scenarios, consisting of three similar houses with different consumption profiles. For each of these scenarios, we used measured consumption data over one day for a residential house and we multiplied the results of one optimization in order to run a simulation for five years of consumption.

We have considered three different energy consumption profiles, as proposed in Fig. 3. For each of these scenarios we used an optimization algorithm where the objective function was to minimize the power supplied by the grid.

As we did not have several solar production profiles we used the same production profile with a corrective coefficient (ratio between the total power consumed by the house over the day and a typical consumption profile). It can be justified by the fact that the bigger the house, the higher its consumption and the higher the potential area for photovoltaic panels. We used the same coefficient to limit the battery capacity, as summarized in the Table 1.

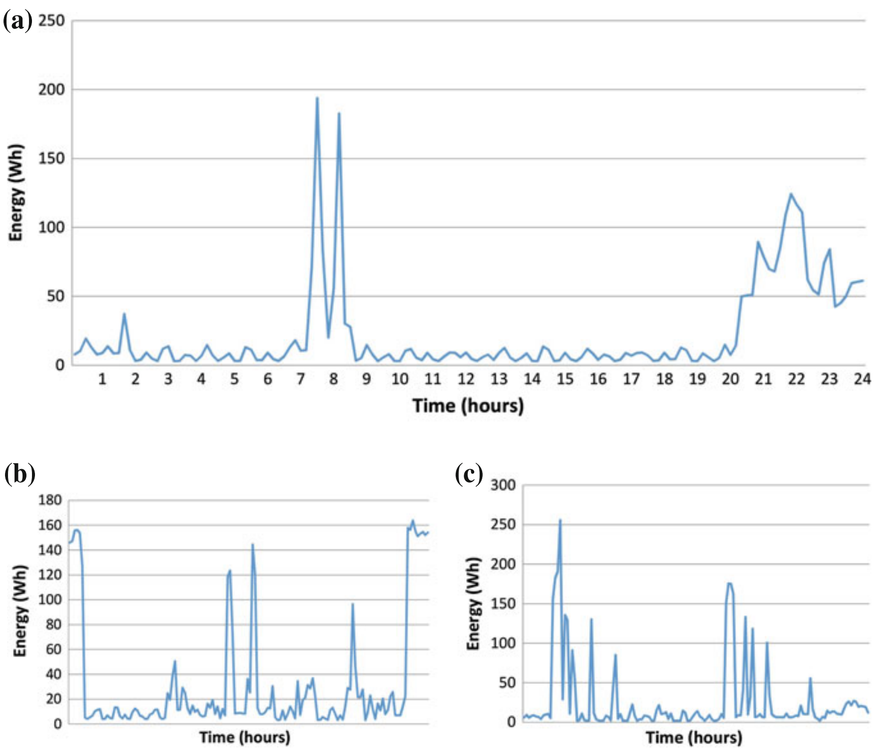

Fig. 3 Load profiles. **a** Load profile A. **b** Load profile B. **c** Load profile C

Table 1 Considered optimized scenarios and their consumption

Load profile (Scenario)	PV coef.	Bat. cap. coef.	*E_grid_tot* (MWh)
A	0.1286	0.25	1.80
B	0.1805	0.1805	4.32
C	0.1480	0.1480	3.74

Table 2 Units description

System	Unit
Electricity	1 kWh of electricity from the grid PV
panels	1 module of 1 kWp, lifetime15 years
Battery	1 battery of 100 Ah, lifetime 10 years

As an example, the optimized load curves obtained in the scenario A are proposed in Fig. 2b. The total energy required from the grid over the five years simulation resulted from the computations is also proposed in Table 1.

4 Inventory Analysis

Usually in a Life Cycle Analysis, the inventory of the environmental impacts and its assessment are two different steps. As this was the very first step of our study, we used the Bilan Produit software, freely proposed by the ADEME, which has now the name "based impact" [11]. Both steps are then conducted at the same time in this software, leading directly to the results.

We conducted our life cycle assessment over a period of 5 years. Therefore we can consider that household appliances will not be replaced. So the three main sources of environmental impact for our system are the electricity supplied by the grid, the PV panels and the battery. We defined the functional unit for these three contributors in Table 2.

In order to get the environmental impact of each contributor, we need to compute first the environmental impacts of one unit and multiply it by the quantity of the contributor to the global functional unit. Values for each indicator are then the sum of the three contributions.

4.1 The Consumption of Energy from the Grid

In our study, we need to model the environmental impacts of the consumption of energy of the household. This means that we need to calculate the environmental impacts related to the consumption of energy taken from the grid. The consumption of 1 kWh (just the utilization phase) of "Low electricity voltage, France" has been chosen from the software, based on the daily average consumption in France.

4.2 The Storage of Energy

For the storage means, we modeled a 100 Ah battery whose lifetime is 10 years and that will be used for 5 years. The functional unit coefficient is then equal to 0.5.

The production phase has been modeled thanks to the information on the components of a typical battery from a study on material needs and raw material costs of batteries [5].

We also took into account the replacement of batteries. We considered a maximal number of charge/discharge cycles of 1000. Based on the optimized load curves, we assumed that the number of cycles is equal to 0.5 per day for the three scenarios. We get the number of replacement of the batteries during the study period (5 years) through the Eq. 1.

$$number_{replact} = \frac{365 * 5}{1000/\text{number of cycles per day}} \tag{1}$$

4.3 The Production of Energy

In order to model the environmental impacts related to the production of energy, we decided to model a PV module made of crystalline silicon normalized to 1 kWp.

Due to a low level of information regarding PV panels manufacture, most of the production steps are unfortunately ignored which represent the most impacting phases of a PV module life cycle. The results of this approximation is used in this work, but should be improved in the future in order to validate that part of the tool.

5 Results

As the functional units for the battery, the PV panels and for the electricity from the grid do not fit with the quantities of our model, we had to multiply the environmental impacts of one functional unit by normalization coefficients.

For comparison purpose the results are then normalized for all environmental indicators. We set the scenario A as reference and the other results are given from this standard.

The radar chart on the Fig. 4 shows these impacts comparison. We observe on the radar graph that the normalized results are bigger of a factor two for the scenario C, which corresponds to the ratio between the electricity taken from the grid of the two scenarios (A and C). We can deduce from this observation that most of the environmental impacts come from the electricity consumption on the grid. Similarly, the scenario B also shows that the electricity grid is the most impacting factor since it has the highest electricity demand and the highest impacts.

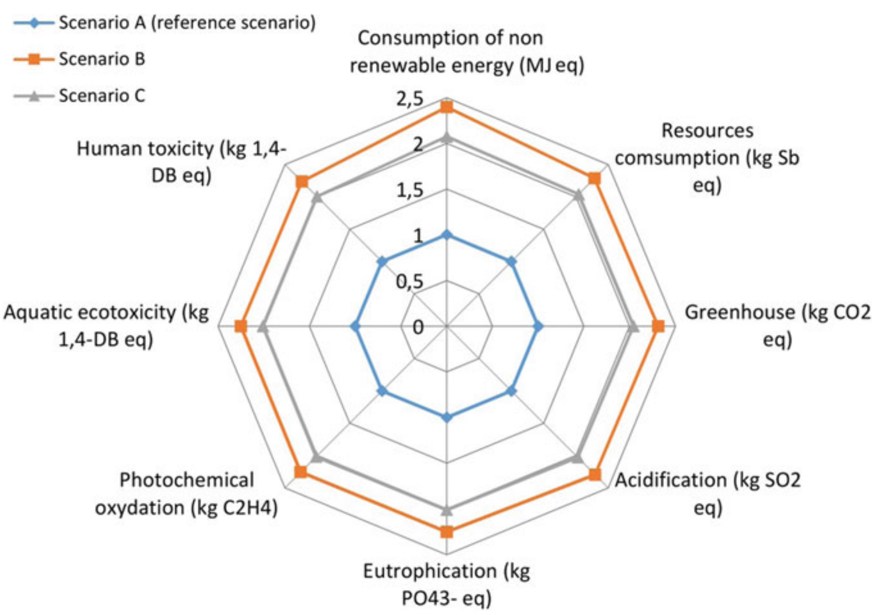

Fig. 4 Comparison of environmental impacts for three scenarios

This comparison leads to the need to better consider the impact of the two other components, PV panel and storage before going further on the use of this tool, especially regarding self-sufficiency of houses.

6 Conclusion and Perspectives

The simulation tool is able to run an optimization on variable load curve and to take into account estimation of environmental impacts for its components and to validate the comparison of the solutions on a numerical basis. From an algorithm point of view, all components modeling are independent and can be improved separately based on further works. The size of the various components (PV panels, storage, grid connection) remains fixed at the moment, but could also be taken into consideration directly in the optimization as variables. Based on the preliminary modeling the tool is operating efficiently and will allow multiple investigation in energy management in the future, especially for comparison on the control of energy sources for Smart Buildings.

Some hypotheses have been made in order to get these first results. The methodology (through an optimization then a comparison of solutions) will not change, but in order to go further, changes have to be made, listed below.

The first approximation we made at the very beginning of our study concerns the choice of the system. Up until now, the house and every electric appliance it contains is only taken into account through the load curve. It could be improved considering more precise model of the loads, and a thermal modeling of the house. The solar profile for the three scenarios (using an arbitrary coefficient), should also be changed depending on the season for example. This will allow to conduct more representative optimization, considering for example a few typical weeks instead of a typical day.

Considering an actual aging of the components (especially the battery) instead of just replacing it after a fixed number of cycles is also to consider in future works.

Finally, the very next step concerns the environmental impacts, especially for the solar panel and the battery. More generally, the optimization have to rely on a more precise modeling of the environmental impacts in order to be able to choose between scenarios and possible solutions, without compromising on the sensitivity of the results. Moving to a commercial environmental impacts database is to be done as a very next step.

However, our study is the first step of a more complete evaluation of environmental performances, which could be developed based on the strong basis of the software able to evolve through the better definition of its components.

Based on that modeling, in order to better qualify the self-sufficiency of houses, through iterative improvements of the models, the local energy control will be optimized and compared between different technologies and usage, in the context of Smart Buildings.

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Demand Response Process in Context of the Unified *LINK*-Based Architecture

A. Ilo

Abstract This paper presents for the first time a unified *LINK*-based architecture for power systems, which provides the harmonization of power system physics and market rules. It is based on the holistic technical model of power systems "Energy supply chain net" and on the corresponding holistic power market model. The last one is illustrated by means of the actual Austrian electricity market. Furthermore, we show how the unification of the market and grid in the same flow diagram increases the uptake of demand response also in the residential, commercial and small business sectors. Their price driven demand response is described in detail.

Keywords *LINK*-paradigm · Unified *LINK*-based architecture · Demand response · Electricity market · Smart grid

1 Introduction

Demand Side Management (DSM) and Demand Response (DR) are processes which try to modify the electricity consumption shape of customers. DSM was coined following the 1970 s energy crisis and since than it is continuously used by electricity utilities as an instrument on increasing efficiency and shaving peaks [1]. It includes almost medium to long term countermeasures. With the technology progress and the rise of distributed generation are opened other perspectives on demand shifting and the reduction of total energy consumption. DR rose and have been dedicated to short-term load reduction in response to a signal from the power grid operator, or a price signal from electricity market.

Indeed nowadays, there is a very slow uptake of DR, particularly in the residential, commercial and small business sectors [2]. The proposed structures are quite complicated and requires big data exchange [3, 4], which causes the increase in the complexity of system operation etc.

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This paper recommends for the first time a new simple structure, named unified *LINK*-based architecture, which under others enables DR process in the residential, commercial and small business sectors. The new operational architecture is based on the *LINK*-Paradigm and the technical and market holistic models. The last one is illustrated by means of the actual Austrian electricity market. DR is described by means of the load reduction in response to a price signal from electricity market.

2 Holistic Model

The integration and the effective use of all available resources on the grid is possible only under a global view of power systems [5]. Figure 1 shows an overview of overall power system models. Figure 1a shows the *LINK*-paradigm, which is the cornerstone of "Energy Supply Chain Net" overall model. *LINK*-paradigm is defined as a composition of an electrical appliance (be a grid part, producer or storage), the corresponding controlling schema and the *LINK* interface [6]. Figure 1b shows the holistic, technical approach of power systems called "Energy Supply Chain Net" [5], which is conceived in two axis:

1. Horizontal
   In the horizontal axis are set interconnected High Voltage Grids (HVG), which actually are operated from Transmission System Operators (TSO).
2. Vertical
   In the vertical axis are set Medium Voltage Grid (MVG) and Low Voltage Grid (LVG), which actually are operated from Distribution System Operators (DSO) and customer plants.

Power grid is arranged in autonomous parts as links in a chain net. Per definition a "Energy Supply Chain Net" is a set of automated power grids, intended for chain links, abbreviated links, which fit into one an-other to establish a flexible and reliable electrical connection. Each individual link or a link-bundle operates autonomously and have contractual arrangements with other relevant boundary links, link-bundles, and suppliers which inject directly to their own grid.

Recently power systems are perceived as assembly of four main components [7]:

1. Power plants (i.e. electricity producer);
2. Storage;
3. Grid and
4. Prosumers.

Based on *LINK*-paradigm, prosumers are conceived of a combination of the three first main power system components and are characterised by a new definition as follows.

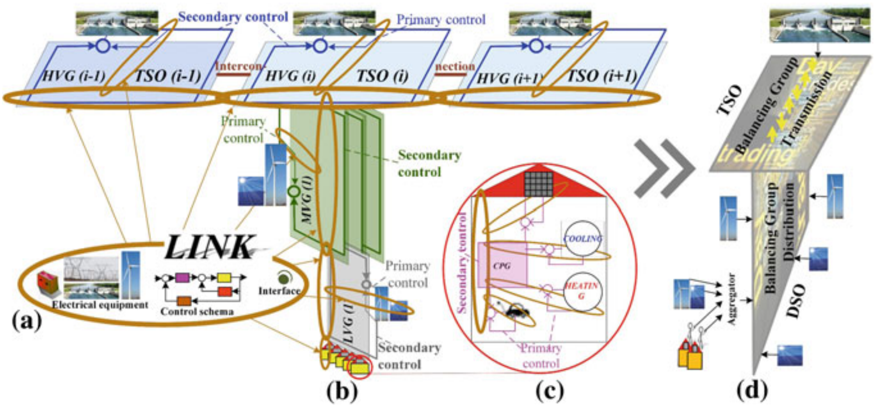

Fig. 1 Overview of overall power system model: **a** *LINK*-paradigm; **b** "The energy supply chain net" model; **c** Customer Plant details; **d** Overall electricity market model

Definition Prosumer is a natural or legal person being owner of small electricity or/and storage facilities which are connected with each other through its own grid. He is connected to the power grid, but the produced electricity is mainly used to supply his own load. He is selling his electric energy surplus, and buying electric energy for own use.

Consumers are treated as a special case of prosumers and defined as follows.

Definition Consumer is a natural or legal person buying electric energy for own use. He is connected to the power grid through its own grid.

Figure 1c shows details of a typical residential consumer. The supplier—i.e. photovoltaic installed on the roof-, storages i.e.—electrical car battery and cooling- and heating systems—are connected with each other via house intern grid—i.e. Customer Plant Grid (CPG).

Therefore there are only three independent main power system components, which create the base for the definition of the *LINK*-based architecture components [6]. This three main architecture components are:

1. Producer-Link;
2. Storage-Link; and
3. Grid-Link.

As in [6] Producer-Link is defined as a composition of an electricity production facility be a generator, photovoltaic, etc., its Primary-Control and the Producer_Interface. Storage-Link is defined as a composition of a storage facility be the generator of a pump power plant, batteries, etc., its Primary-Control and the Storage_Interface. While, the Grid-Link is defined as a composition of a grid part, called Link-Grid, the corresponding Secondary-Control and Grid_Interface. Each architecture component has also its own operator—i.e. the Producer-Link has the Electricity Producer Operator; the Storage-Link has the Storage Operator (StO) while the Grid-Link has the Grid-Link-System_Operator.

Figure 1d shows an overview of the overall electricity model, which is a mirror of the technical overall model. Based on this model not only the TSO [6, 8], who operates on the horizontal axis of power systems, but also the DSO, who operates on the vertical axis of power systems, will communicate directly with the market and take over the task of load-power injection balance. And in fact two of the main tasks of Grid-Link-System_Operator (Grid-Link-SO) defined in [6] are: Facilitation of an effective and well-functioning retail market and load-power injection balancing in real time. The owner of the decentralised appliances may participate in to the market directly or through an aggregator.

3 Unified *LINK*-Based Architecture

LINK-paradigm applies particularly to network operation. When the structure of electricity supply changes so much, due to many decentralised generation units, each with the possibility to interfere with the system operation at all voltage levels, then it is needed a new architecture in order to utilize this flexibility, so that the power system operation can remain reliable. The new operational architecture of power systems should guarantee that it performs as expected by unifying the operation processes and systematising the execution of operational tasks.

Definition The unified *LINK*-based architecture is an architecture of power systems in which all relevant components like electricity:

– Producer (independent from the used technology or size, ex. big power plants, decentralised generations, etc.)
– Storage (independent from the used technology or size, ex. pumped power plants, batteries, gas systems etc.)
– Grid (including all voltage levels—i.e. high-, medium- and low voltage grid-) and
– Market are merged into one single structure. This architecture unifies all interactions within the power system itself and between it and market thus creating the possibility to harmonize them.

Figure 2 shows an overview of the unified *LINK*-based architecture of smart power systems. Operation or study Grid-Link communicates via technical interfaces T with other neighbour Grid-Links, and Producer- and Storage-Links which are connected to its own grid. Technical interfaces are already well defined [6]. Their communication with the electricity market is foreseen through the market interface M. The illustration of market interface M is done based on the Austrian electricity market [8]. Some of the most prominent participants in this market are:

– Control Area Manager, CAM → responsible for load-frequency control within its control area
– System Operator, SO → operator of transmission or distribution grid
– Supplier → commercial provider of electric energy

– Consumer → buyer of electric energy for own use
– Clearing and Settlement Agent, CSA (balance group coordinator) → responsible of organising, clearing and settling of balance within a control area
– Balance responsible Party, BRP balance group representative → an entity representing a balance group vis-à-vis other market participants and vis-à-vis the CSA.

In Austrian electricity market were introduced balance groups to enable consumers, generators, suppliers and wholesalers to trade or conclude deals with each other [8]. Whoever takes electricity off the power grid, feeds in or trades must be a member of a balance group. BRP balances the load within the balance group. CSA takes care for load balancing within the control area, which includes more than one balancing group, up to the intraday trade. In the following CAM ensures the system stability in real time by performing the load-frequency process, which in reality is handled by TSOs. Consequently, TSO assumes a new role, the one of CAM. The number of the data that should be sent to CAM or rather to TSO is immense [7, 8]. Beside the different contracts types—i.e. utilisation-, supply- or storage contract -, meter readings and bills, market participants exchange schedules for electricity trading [8]. Here it should be noted that there are two types of schedules:

1. Internal
   Internal schedules for electricity trading between balance groups in the sane control area
2. External
   External schedules for electricity trading between balance groups in different control areas.

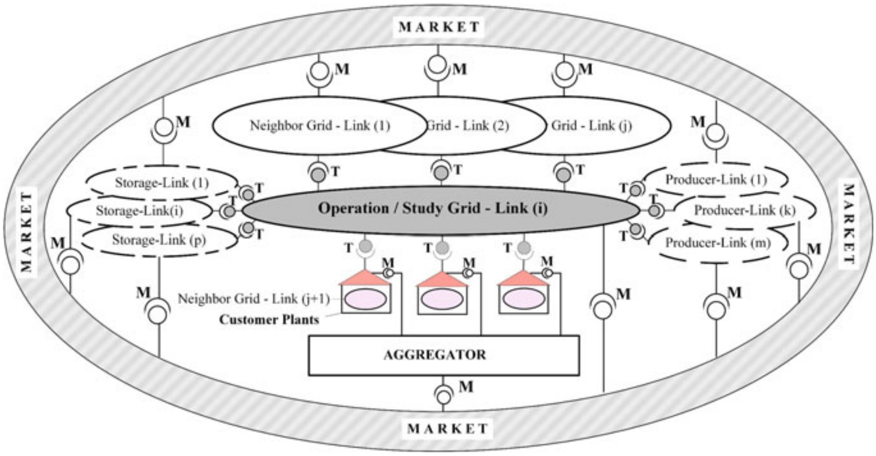

Fig. 2 Overview of the unified *LINK*-based architecture of smart power systems

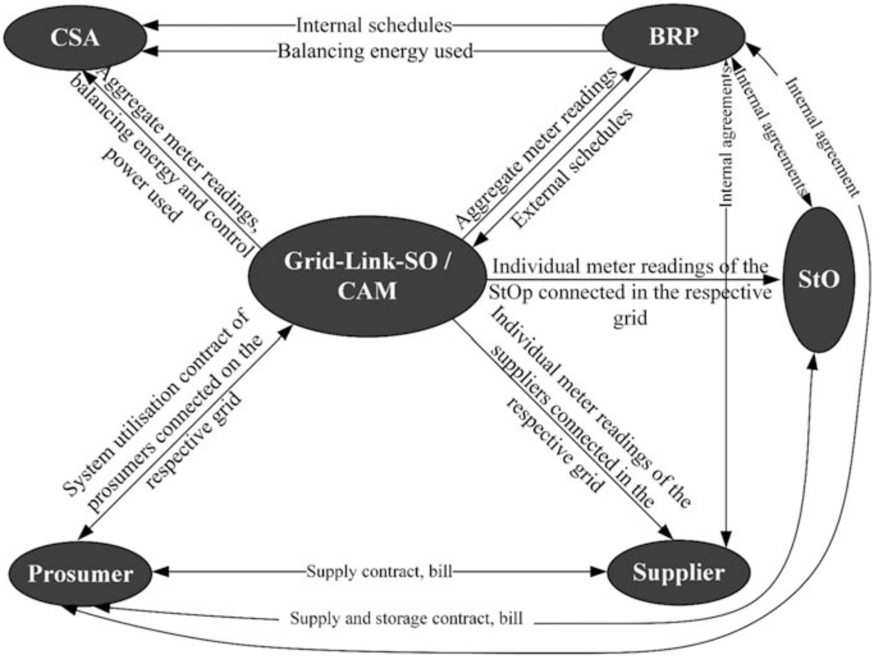

Fig. 3 Schematic representation of contractual relations and information exchange among market participants in case of unified *LINK*-based architecture

Figure 3 shows a schematic presentation of the Austrian electricity market model in contest of the unified *LINK*-based architecture. In this figure are shown the contractual relations and information exchange among market participants. Market participants and their roles remain almost the same as in [8] up to the roles of TSO and DSO combined with CAM. With the unified *LINK*-based architecture are introduced three crucial novelties in the electricity market model:

1. Storage Operator
   Storage operator rice is a logical consequence of the new technological developments and is defined as follows:

Definition Storage Operator, StO is a natural or legal person that provides and stores electric energy to or from other natural or legal persons.

StO must participate to a balance group, have supply and storage contracts with the prosumers, and receives the individual meter readings from the grid, where it is connected.

2. Consumers are transformed to prosumers
   In recent years, many consumers have gradually been transformed into prosumers. Their inclusion on the market model is essential for the fair development of the electricity market.
3. Adoption of the CAM role
   The adoption of the CAM role is crucial for a secure, reliable and efficient operation of power systems by fulfilling the stringent requirements of data privacy and cyber security. In the new market model each of the Grid-Link-SO—i.e. TSO and DSO—assumes the new role CAM. That means that each Grid-Link-SO have also the CAM role, and is responsible for the load balance process in their own control area up to the real-time time frame. The technical realization is realistic, because a secondary control for the active power and frequency is designed per each Grid-Link type [4, 6].

In this new electricity market model the scheduling process is foreseen to remain the same as described in [8] with the only difference that the pumping schedules should be converted to storage schedules.

4 Price Driven Demand Response

The unified *LINK*-based architecture allows the properly launch of demand response. The emergency DR—i.e. load reduction to alleviate overloading in high voltage grid, which is triggered from the power grid operator—is described in [6]. Heir we will focus on DR to a price signal from electricity market.

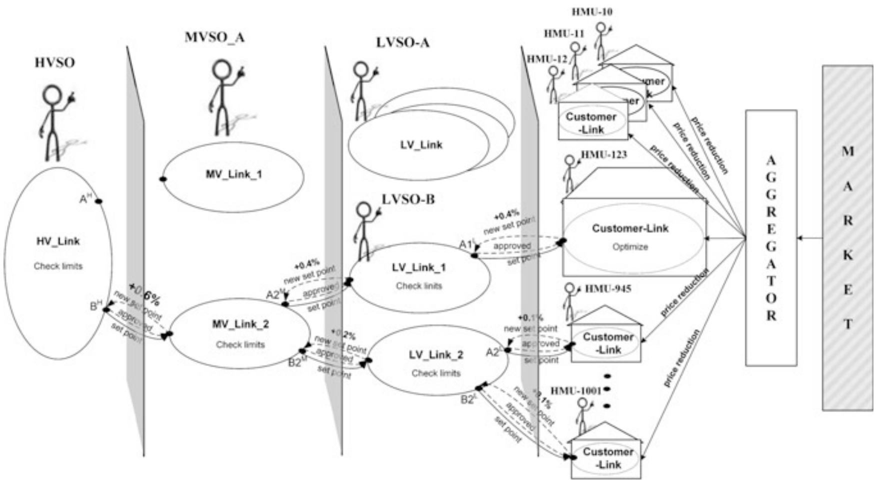

Fig. 4 Information flow during price driven demand response

The activation of the residential, commercial and small business sectors, which join the real-time pricing demand response through already concluded contracts, may be triggered at any time. Their degree of participation in the demand response process may be different depending on the time of the day, duration interval, price value, etc. Let's assume that conditioned from weather and the minimal load consumption there do exist a surplus of the electricity in the market, which causes a price decrease. Figure 4 shows the information flow during price driven demand response. The new, reduced price is sent via the aggregator through the market interface M to the House Management Units (HMU), [6], of each customer. Figure 5 shows a detailed view in customer- and low voltage level of the information flow by a price reduction signal. HMU after having calculated the possibilities of demand increase in the house, sends a request to increase the consumption by 0.4% via the technical interface T to the boundary node $A1^L$ of LV_Link_1. After receiving the request for the new set point, Low Voltage Grid-Link System Operator B (LVSO-B) check power flow limits in the own Grid-Link. In the case that the power exchange in the boundary node $A2^M$ with the Medium Voltage_Link_2 is affected, he should pass over the request on to the Medium Voltage System Link-Grid Operator-A (MVSO-A). After have collected all incoming requests MVSO-A calculates power flow in the own Grid-Link. Based on calculations results he sends on to the High Voltage Grid-Link System Operator (HVSO) a flow increase request of 0.6% in the boundary node B^H. After have collected all incoming requests HVSO performs all necessary calculations—i.e. power flow, n-1 security, etc.—After having checked all limits HVSO approves the new set points and notify MVSO-A. The last one approves the new set points in boundary nodes $A2^M$ and $B2^M$ and notifies LVSO-B. The last one approves the new set points in boundary nodes $A1^L$, and $A2^L$ and $B2^L$ and notifies the respective HMUs, which execute the demand increase.

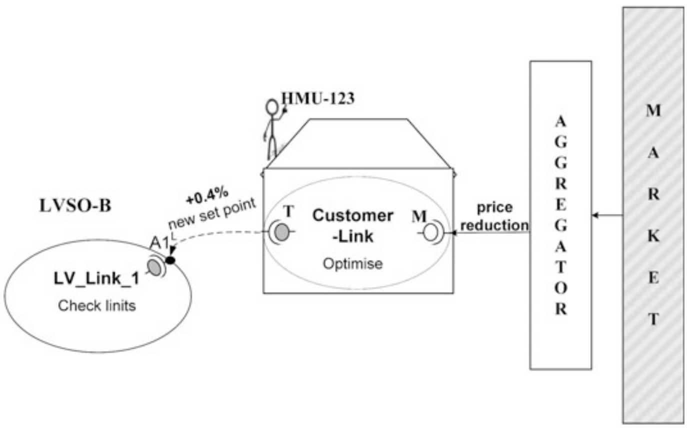

Fig. 5 Detailed view of the information flow by a price reduction signal (customer and low voltage level)

The one flow diagram of demand response in emergency- and price driven cases enable residential, commercial and small business sectors to perceive transparent energy prices and to contribute in the reliable and efficient operation of electric power system.

5 Conclusions

The unified *LINK*-based architecture merges producers, storages, grid and market into one single structure. Prosumers and Storage appliances are newly, more precisely defined. The market *LINK*-based model is extended with new actors and their old roles are redistributed. The demand response for residential, commercial and small business sectors is described in a unified flow diagram. Demand response can be triggered from the grid operator in emergency cases or market through different price incentives.

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Part III
Components

Eco-design in Oil Immersed Transformers

Pablo Cirujano and Enrique Otegui

Abstract All electrical products, and even all products, have an impact on the environment because of its production, its activity and the end of its active life. Power transformers are one of the most important components of the electrical system and the impact they produce has to be taking into account because of the materials they are composed by and their losses or efficiency. The New European Regulation 548/2014 on eco-design of power transformer fixes the maximum admissible losses and so the efficiency, but all the rest of the aspects related to the impact of transformers should be taken into account State of the art Power Transformers need to take into account: (a) consumption of natural resources used in the manufacturing, (b) environmental impact of the manufacturing process itself, (c) Use of eco-friendly insulation oils, preventing potential contamination of water and soil, (d) Energy losses in service, (e) Contribution to an efficient use of energy in a smart, highly penetrated for renewable generation network, (f) Minimum environmental impact of the end of life process and valorization of dismantled components. The paper considers how some of these aspects are taken into account in a modern, state of the art power transformer design. ORMAZABAL manufactures a wide range of dielectric liquid immersed distribution and power transformers, compliant with all of the requirements in current international regulations and with a range of powers from 25 to 5000 kVA and insulation levels up to 36 kV. In addition, its portfolio includes special transformers up to 72.5 kV and 10 MVA [1].

Keywords Transformers · Eco Design · Environmental impact · Life cycle · Efficiency · Resources · Smart grid · Renewables

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1 Introduction

Distribution and small power transformers are those which function is connecting the medium/high voltage distribution grid to the medium/low voltage one to satisfy the consumers demand in the proper voltage levels.

This work is focused on a type of transformers extensively used: oil immersed transformers.

Transformers environmental impact analysis has three main parts:

- **Life cycle analysis**. Environmental impact of the product taking into account the whole life cycle. It is the impact produced when an additional unit of the product is created. This paper is going to focus in this part in the existence of the product itself not to its activity or service. It involves the raw materials extraction, manufacture of components, manufacture of product, waste landfill and recycling.
- **Activity environmental impact**. It is related to the energy consumption of the product (losses in the transformer case) and the emissions (noise, radiations, oil leakages…). This part is related to the New European Regulation 548/2014 regarding the efficiency in transformers.
- **Importance of the distribution transformer in smart grids and distributed generation integration**. New smart distribution transformers with on load voltage regulation and monitoring will be needed to allow the development of the smart grids and the integration of the distributed generation.

2 Lyfe Cycle Analysis

ORMAZABAL, as a transformer producer, develops transformers that satisfy the highest level of efficiency focusing in the following details [1]:

- Dielectric Liquid completely immersed Hermetically-Sealed Transformers even over 3150 kVA:
  - No expansion tank needed, so less dielectric liquid used than in other types of transformers and less use of raw materials.
  - No contact between the dielectric liquid and external agents (air, humidity, pollution, etc.) what prevents deterioration of the dielectric's characteristics and implies Low-level maintenance
  - Minimal risk of leakages by the tank robustness (high quality materials), welding processes carried out by qualified staff and leak tests performed in all transformers.
- Minimal Environmental Impact by:
  - Use of highly-recyclable materials
  - Rationalisation in the use of raw materials

– Optimised transformer dimensions
– Optimum consumption of raw materials by materials selection and maximisation of their characteristics
– Low electrical energy consumption by advanced technology in design, manufacturing and testing and minimal loss transformers.

2.1 Description of the Product

The application of the distribution and small power transformers is mainly within urban areas for domestic consumption, industrial customers in industrial areas and rural areas. With given secondary voltage, distribution transformers are usually the last in the chain of electrical energy supply to households and industrial enterprises [2].

Oil immersed transformers are composed mainly by the following parts:

1. **Windings**. Of copper or aluminum. They have two parts:
   (a) Medium voltage coils. Because they work with lower currents and higher voltages they are made of copper or aluminum insulated wire and additional insulation of cellulose.
   (b) Low voltage coils. Because they work with higher currents and lower voltages, they are usually made of copper or aluminum band and cellulose insulated turns.
2. **Magnetic core**. It is made of ferromagnetic metal such as iron. Laminated magnetic cores are made of thin, insulated iron grain oriented sheets (there is an alternative core technology called Amorphous still not used extensively in Europe).
3. **Tank and structural components**. They are made of iron. The tank is made by welding parts to the fins (refrigeration elements). The structural components normally are used in the magnetic core as the jokes. The tank also includes paint and painting threatments.
4. **Pressboard**. It is normally structural insulation, normally in sheets and presspaper in rolls.
5. **Oil**. Transformer oil, or insulating oil, is a fluid that is stable at high temperatures and has excellent electrical insulating properties. Its functions are to insulate, suppress corona and arcing, and to serve as a coolant. There are several types of transformer oil [3]:
   (a) **Mineral oil**. It is a highly-refined oil from petroleum, a by-product in the distillation of petroleum from crude oil. It has a density of around 0.8 g/cm3. Mineral oil is a low toxicity fluid and is 25% biodegradable. However, the low fire point, at 150 °C, requires additional protection (and costs) for buildings and equipment to reduce fire risk.

(b) **Silicone oil**. Today, non-toxic, stable silicone-based or fluorinated hydrocarbons are used, where the added expense of a fire-resistant liquid offsets additional building cost for a transformer vault. It implies low toxicity but very low biodegradability also remaining stable in nature for a very long time.

(c) **Vegetal oil**. Combustion-resistant vegetable oil-based dielectric coolants esters are also becoming increasingly common as alternatives to mineral oils. Esters are non- toxic to aquatic life, readily biodegradable, and have a lower volatility and a higher flash points than mineral oil. It is a natural ester made from edible seed oils and is greater than 99% biodegradable in standard test methods. The Spanish Petrochemical company REPSOL developed, with the collaboration of ORMAZABAL, the BIOELECTRA biodegradable oil based on food-grade sunflowers oil.

2.2 Life Cycle Analysis

LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service [4].

The LCA is composed by the following steps that imply energy consumption and emissions [5]:

- Raw Material extraction
- Manufacture of components
- Manufacture of product
- Use service 📫⌨ Analyzed apart because it depends on the put on service
- Waste landfill and recycling

The parts of the Life Cycle Analysis of oil immersed distribution are the following:

2.2.1 Raw Materials Extraction

To simplify this study we are going to focus the environmental impact of the transformer in copper, steel and oil.

The impact of **copper extraction** is due to erosion, loss of biodiversity, contamination of soil, groundwater and surface water by chemicals from mining processes, forest logging, and affection to health of local population. Ore mills generate large amounts of waste, called tailings, which are perhaps their largest environmental burden. 99 tonnes of waste are generated per tonne of copper. These tailings can be toxic [6].

In terms of emissions in copper production the aprox figures are:

- **CO_2 eq emissions**: 6.5 MT CO_2 eq/MTF (MTF = metric Ton refined copper)

The iron impact is due to the ore **iron extraction** and the Ironmaking. Iron ores are rocks and minerals which yield metallic iron on extraction. Iron is found in numerous forms like magnetite, siderite, goethite, limonite etc. Steel is made from a raw material called Pig Iron. Pig Iron is also made from Iron Ore. Mining of Iron depends and varies according to the type of ore which is being mined.

The average crustal abundance of iron is 5% by weight. The iron content of soils is typically in the range of 0.5–5%, and is dependent upon the source rocks from which the soil was derived, transport mechanisms, and overall geochemical history [7]. Ironmaking refers to the reduction of metallic iron from the oxide form in which the element is found in nature. The process is carried out in a blast furnace that entails environmental impacts that are hard to avoid [8].

In terms of emissions in steel production the aprox figures are:

- **CO_2 eq emissions**: 2 MT CO_2 eq/MT of steel [9]

For the **oil extraction**, the construction of the producing well, has a relatively small footprint because the lower amount of solid material to be moved and so that, the business of extracting fluids from the earth is a less disruptive to the earth's surface than the extraction of solids [10]. However, its potential environmental impact can be much larger. First, oil and gas are not the only fluids that the tube conducts to the surface. Huge quantities of water, bearing complex mixtures of salts including those of toxic metals, as well as toxic organics, both from the natural formation and from additives to facilitate production, also issue from the wells.

In terms of emissions in oil production the aprox figures are:

- **CO_2 eq emissions**: 0.06 MT CO_2 eq/MT of oil [11]

It is going to be considered that the **rest of raw materials extraction** implies a 10% in CO_2 equivalent emissions of increase over the main materials analyzed before.

2.2.2 Manufacture of Components

The manufacture of components from raw materials consists of the following parts:

- **Insulated Copper wire.** Wire drawing is a metalworking process used to reduce the diameter of a wire by pulling the wire through a single, or series of, drawing die(s) [12–14].
  - **CO_2 eq** emissions: 0.39 MT CO_2 eq/MT of Cu wire
- **Copper band laminated.** Rolling operations are mechanically similar for both aluminum and copper. The primary purpose of a nonferrous metal rolling operation is to reduce the gauge (thickness) of the metal work piece and form it

into a useful shape. The two basic types of rolling processes are hot and cold rolling which are used in most nonferrous rolling industries. As stated previously, hot rolling reduces metal ingots to medium gauge where further reduction takes place via cold rolling to strip, foil, and light-gauge sheet sizes. This section discusses both hot and cold rolling processes and the equipment employed during those operations [15].

  – **CO_2 eq** emissions: 0.78 MT CO_2 eq/MT of Cu band

- **Steel production.** Steel mills turn molten steel into blooms, ingots, slabs and sheet through casting, hot rolling and cold rolling [16]. An integrated steel mill has all the functions for primary steel production but we focused here in roughing rolling/billet rolling (reducing size of blocks) and product rolling (finished shapes).
  – **CO_2 eq emissions**: 0.85 MT CO_2 eq/MT of cold rolled steel aprox [17]
- **Core sheet production.** It is a particular application of the steel production seen in the previous step but Ecoinvent database gives a difference of about 4–5% of increase in emissions of Electrical Grain Oriented Steel (GOES) than regular iron [18].
  – **CO_2 eq emissions**: 0.9 MT CO_2 eq/MT of GOES aprox
- **Oil refining and treatment**
  – **CO_2 eq emissions**: 0.4 MT CO_2 eq/MT of oil aprox [19]
- **Rest of Raw materials.** It is going to be considered that the CO_2 equivalent emissions of the rest of raw materials production implies a 10% of increase over the main raw materials production.

2.2.3 Transformer Construction Process

The main environmental impact in this part is the production of the transformer tank because the rest of the processes are assembling steps.

Tank manufacturing involves:

- Cleaning. The iron is treated to remove oils and lubricants and also particles creating residues.
- Welding.
- Painting. Depending on the use of water paintings or dissolvent paintings its impact is different.

During the transformer production phases there are several with a higher consumption of energy like curing and drying processes, cutting steel sheet and filling under vacuum, but the impact compared to the materials extraction and components manufacturing is much lower. We are going to consider an increase of 10% of MT CO_2 eq over the whole result.

2.2.4 Recycling and Waste Landfill

Most natural resources and emissions in the end of life scenario have negative value, as those are reclaimed as environmental profit.

The final resources are materials to recycling and energy resources:

- Coal (energy resource)–3 kg/kVA
- Cu (material resource)–0.07 kg/kVA
- Fe (material resource)–0.8 kg/kVA
- Gas (enery resource)–0.25 kg/kVA
- Oil (energy resource)–1.21 kg/kVA.

3 Working on Service Phase

The environmental impact of a transformer working has two parts:

- **Energy consumption**. Transformers produces two types of energy losses turned into heat:
  - No load losses. Produced in the magnetic core.
  - Load losses. Produced by the joule effect in the conductors under load.
- **Emissions**. The emissions are mainly:
  - **Noise**. Caused by the magnetostriction phenomenon in the magnetic core which consists on a vibration of the steel sheets that produces noise. It depends on the induction level and it can be reduced by design, reducing the nominal induction level.
  - **Magnetic Fields**. Mainly in the low voltage connections because of the high current level that produces magnetic alternate field around. They can be reduced by shielding.

ORMAZABAL is really focused in reaching the highest sustainability level, understood as the best compromise between satisfying social demands, caring for the environment and financial aspects. Caring for the Environment addresses ORMAZABAL to a reduction in the volume of dielectric liquid, minimal dimensions as possible, minimal losses, reduction of risk of oil leakage, being non-aggressive for the surrounding environment.

ORMAZABAL complies with the requirements of the Eco-design directive from the European Commission (No 548/2014) that defines the guideline for the environmentally friendly design of the transformers in Europe. This regulation applies to all the transformers placing on the market or put into service from July 2015 throughout the European Union and doesn't affect the products to be exported outside Europe. The Ormazabal distribution and power transformers are being developed to contribute to commitment of this directive, that is, to improve energy efficiency and environmental performance [1].

4 Role in Higly Penetrated Distributed Generation

Taking into account the explained before regarding the environmental impact of the transformers due to the raw materials consumption and the CO_2 equivalent emissions in the transformation of the raw materials, in the manufacturing activity and the emissions due to the losses on service, it is necessary to know the positive impact also of the transformers to facilitate the connection to the network of distributed generation.

Distributed generation reduces the amount of energy lost in transmitting electricity because the electricity is generated very near where it is used, perhaps even in the same building. This also reduces the size and number of power lines that must be constructed.

Solar PV and wind power both have intermittent and unpredictable generation, so they create many stability issues for voltage and frequency. These voltage issues affect mechanical grid equipment, such as load tap changers, which respond too often and wear out much more quickly than utilities anticipated, and especially as closer as possible to the generation point. This implies voltage compensation in distribution transformers [20].

ORMAZABAL, concerned with solving these problems, has developed the product transforma.smart; smart transformers with an on-load tap changer (OLTC) capable of regulating the low voltage. This smart transformer keeps the voltage stable in distribution grids by compensating fluctuations in MV and dynamically reacting, at low-voltage, to distributed generation and load changes.

The innovative design of the ORMAZABAL OLTC, OLATC, allows a compact smart transformers design keeping a similar footprint to that of conventional transformer [21].

This ORMAZABAL solution, focused in sustainability, is a basic tool for renewable energy integration, CO_2 footprint reduction, reduction in raw materials and ready to work in combination with biodegradable vegetal dielectric liquids. This solution is also focused in reliability because its maintenance free, proven vacuum bottles technology, balance mechanical operation and service life equivalent to an off load tap changer transformer.

The first range of this smart transformer reaches 800 kVA and 24 kV.

5 Conclusions

LCA of power and distribution transformers reveals an important impact in terms of raw materials consumption, CO_2 equivalent emissions due to materials extraction, materials conversion, logistics, manufacturing processes, losses and end of life waste landfill and recycling.

ECO Design transformers according to the New European Regulation Directive 548/2014 allow the reduction of losses on service, so CO_2 eq emissions, but this losses reduction implies a CO_2 eq emissions increase in the first steps of LCA because of the higher need of raw materials for this losses reduction [20]. The increase of CO_2 emissions per transformer manufactured is around 20% but this is compensated in the first year of service. In 30 years of expected life, 40–50 Ton of CO_2 eq emissions will be reduced just in no load losses in a 630 kVA transformer, comparing an DoCk and a AoCk [22].

Two important contributions of ORMAZABAL transformers difficult to be assessed are:

- Positive impact in CO_2 eq emissions reduction using vegetable oil in its ORGANIC transformers instead of mineral oil
- Positive impact in CO_2 eq emissions reduction by the possibility of integrating distributed renewable generation reducing the grid impact of voltages unbalances.
- Positive impact in CO_2 eq emissions reduction designing transformers hermetically sealed and integral filling with less amount of iron and oil than the ones with rigid tank, radiators and expansion tank.

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Low Inductance Fuses for Protection and Disconnection in DC Networks

Jean-Louis Gelet and Jean-François De Palma

Abstract Development of renewable energies will be possible because of progress in electrical power converters. But, even if reliability of converters is highly secured, some mis-operations or failures may occur. Generally, these mis-operations and failures lead to a high current short circuit and then, electrical fuses are able to bring an efficient solution to protect equipment and persons. Unfortunately, fast-acting fuses are components which size depends on rated current (cross section) and voltage (length) they have to cut: higher is the voltage, longer is the fuse. And a longer fuse will increase the inductance of the circuit, and then increases the commutation-time of electronic switches. Engineers are facing the problem of choosing between: (a) Accept to not protect the equipment. (b) Protect the equipment but reduce its performances. (c) Not develop any converter. Mersen is studying fuses, specifically designed for this kind of converters, both guarantying safety of equipment and keeping the inductance at low values. Of course, these fuses will not reduce energy consumption by themselves, but they are crucial components for equipment that will reduce energy consumption." The paper will present the different kinds of faults depending on the source, i.e., internal fault, external fault and up-stream fed fault. It will also describe what will be the specificities needed for a protection device, i.e., fuse. And what is the investigation-plan carried out by Mersen for proposing the right fuse.

Keywords Inverter · Converter · Electrical protection · Fuse · Inductance

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1 Short Circuit Faults in DC Networks

Topologies for electrical equipment are generally organized around a DC bus, fed by one or several sources and supplying power to inverters. In case a semi-conductor in an inverter goes faulty, a short circuit occurs in this inverter fed by the capacitor located ahead of the inverter (so called internal short circuit). Moreover, as the inductances between all the parallel inverters, through the DC bus, are very small, capacitors of these inverters may start to feed the short circuit within a short time (total or external short circuit). Then the fuse in charge of internal protection within the faulty inverter will also have to bear actions from parallel capacitors (Figs. 1 and 2).

A third case concerns feading by the up-stream side of the bus (up-stream fed short-circuit) (Fig. 3).

2 Fuse Protection for VSI Converters

When the first semi-conductor components came out at the end of the 50's, they were included into converters as simple as diode-bridges. At that time, engineers were confronted with their certain weakness under short-circuit conditions. So they introduced the thermal constraint that semi-conductors must be able to withstand without deterioration:

Fig. 1 Internal short circuit

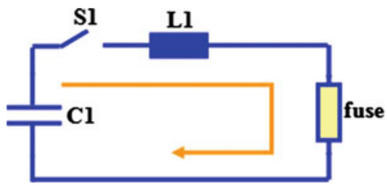
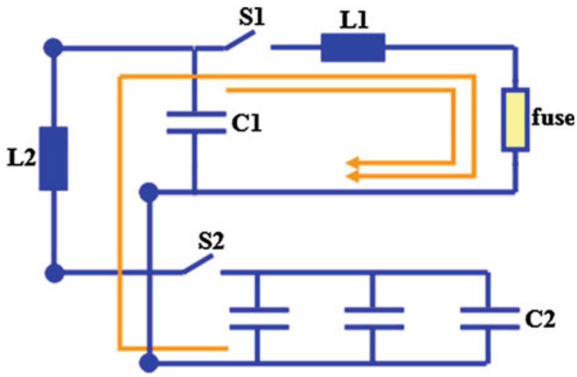


Fig. 2 Total short circuit



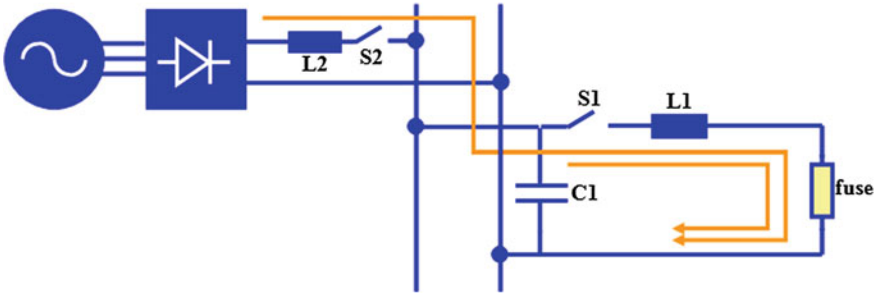


Fig. 3 Up-stream fed short circuit

$$\int I^2.\mathrm{d}t$$

On both side of the Atlantic Ocean, companies that would merge years later into MERSEN, developed ultra-fast fuses to stop the current before any damage to the electronic component, i.e., diode or thyristor. Later, during the 80's, new semi-conductors emerged, the most common ones being GTO's and IGBT's. The latter presented the advantage of reducing losses at commutation and on-state voltage and therefore watt-losses. On the other hand, the permitted thermal constraint of these components was decreased and fuse protection of their junction became difficult.

Nevertheless, even if it is not possible to guarantee full protection of an IGBT under short-circuit, it is absolutely crucial to ensure that its failure will not cause a more dramatic deterioration of the equipment as a whole. Particularly, an explosion of the IGBT-case would damage other components, completely destroy the installation and lead to long downtime, large operating losses, and even more danger to people. Under these conditions, the fuse takes over and ensures excellent protection—providing it is correctly designed and characterized. As early as 1985, MERSEN published a specific method for characterization and selection of fuses for VSI-converters in Technical Leaflet NT SC 120.

The principle of this method is founded on the beside circuit diagram, considering that in case of short-circuit in the downstream leg, and because of the very low inductance l, capacitor C will be discharged very quickly, i.e., with a very high di/dt, MERSEN's engineers defined and calculated specific characteristics for the protection fuse:

- Upm, the maximum value of Up that the fuse can accept, Up being the voltage across the capacitor at the end of the fuse prearcing-time
- The pre-arcing I^2t.

3 Determination of Upm

Since 2012, IEC-standard 269-4 has introduced the concept of a fuse for VSI applications, i.e., designed for inverters fed by a voltage-controlled source. This standard requires checking the VSI-voltage-rating of these fuses by tests under current I1, in DC conditions, with time constant between 1 and 3 ms (See IEC 269-4, Table 106). These conditions required by IEC standard are slightly different from actual conditions in case of fault-current in VSI-inverters. Mainly, in an actual VSI-inverter the value of Up can be much lower than the value E of the DC power supply, whereas in case of operation in DC conditions and low time constant τ, Up is at the level of the DC power supply voltage, including ripple factor[1].

Then, considering only the DC power supply voltage can be very pessimistic if prearcing-time is long enough to ensure a high voltage decrease. That leads to choice a higher rated voltage fuse, i.e., geometrically longer than expected and then introducing a high inductance value in the circuit. In order to have a better knowledge, MERSEN developed a specific high di/dt test bench with following performance data.

4 Risk of Re-Ignition—Proposal for an Additional Characteristic Em

It is possible to demonstrate that in case of short-circuit fault within a leg of a VSI-inverter, the capacitor will be re-charged by the upstream source through the inductance λ (see Fig. 4.) The more the capacitor is discharged during the short circuit, the more the voltage across it will be high. There is actually a risk of re-ignition of the fuse in operation, depending on many parameters (Figs. 5, 6, 7, 8 and 9 and Table 1).

MERSEN's leaflet NT SC 120 introduced Em, the maximum value of E that the fuse can accept, E being the initial voltage across the capacitor. Some restrictive hypothesis must be respected:

a. Inductance λ of the upstream circuit is large versus the inductance L of the discharge circuit of the capacitor C ($\lambda \gg L$)
b. Discharge current of C is highly oscillatory
c. Oscillation period T of the discharge current is less than 10 ms
d. Fuse melting occurs after less than T/6, i.e., the voltage at the terminals of the capacitor doesn't go under half of the initial voltage; this is due to the fact that voltage during discharge follows a law in cos ωt and cos $\omega T/6 = ½$.

[1]In order to partly take into account the fact that the given value of the DC-voltage is generally the RMS value of the rippled trace, Table 106 of IEC-269-4 requires that the mean value of recovery voltage is in the range 110^{+5}% of the rated voltage.

Fig. 4 Typical diagram of a VSI-inverter's leg

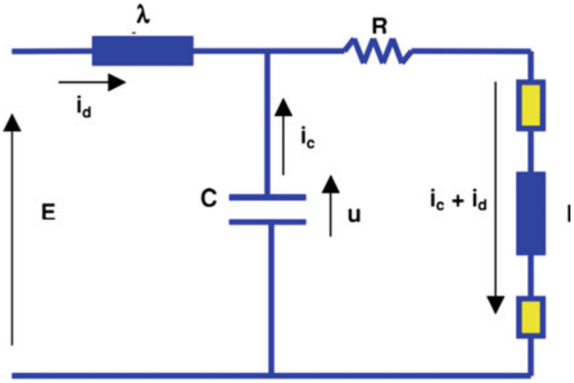


Fig. 5 Operation under VSI conditions, i.e., capacitor discharge

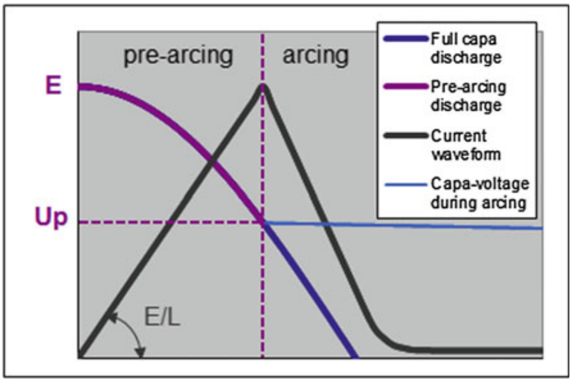


Fig. 6 Operation under DC conditions with τ = L/R

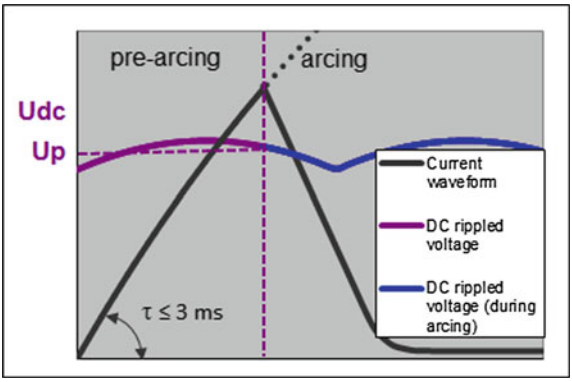


Fig. 7 General overview of the high di/dt test bench at MERSEN's Saint-Bonnet de Mure Lab (France)

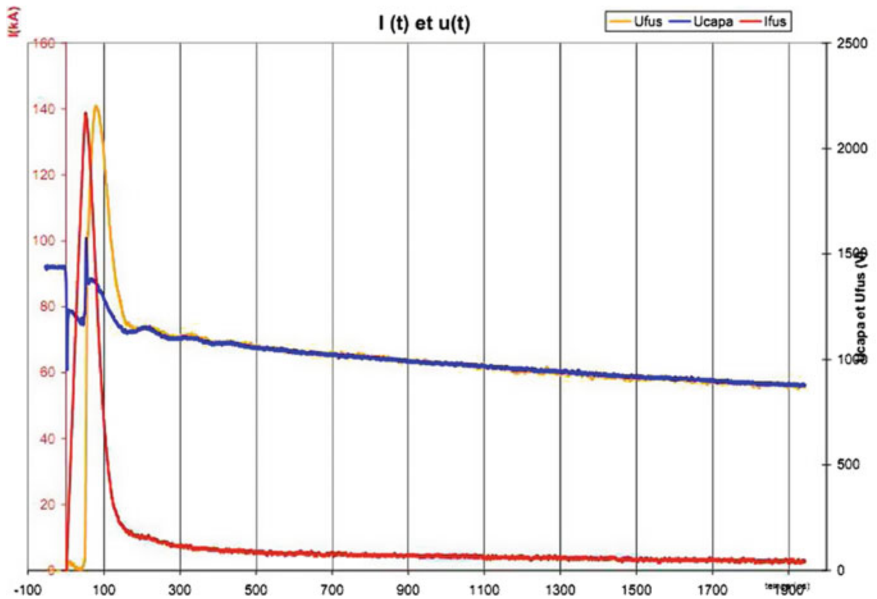


Fig. 8 Typical oscillogram of fuse operation under VSI conditions

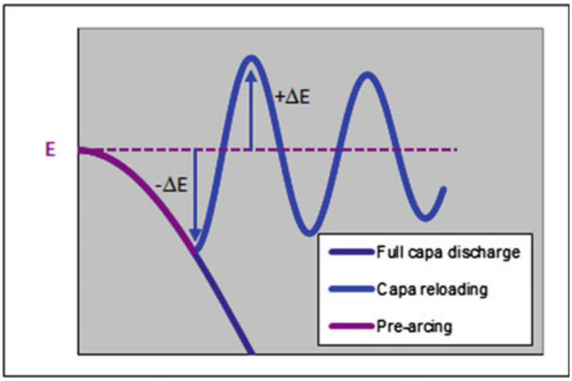


Fig. 9 Voltage across the capacitor can increase up to E + ΔE

Table 1 Characteristics of MERSEN's high di/dt test-bench

Couplings	Capacitances	Available di/dt
2 kV	31.2 mF	4000 A/μs
4 kV	7.8 mF	5000 A/μs

5 MERSEN'S Research-Program

The above hypothesis about inductance λ, pulsation ω and prearcing-time were probably realistic in the past as it is proven by years of experience. They allowed to avoid taking into account the possibilities of re-arcing of the fuse. But, nowadays more and more applications are based on the principle of a DC-bus feeding a number of inverters in parallel. In order to propose solutions for protection against short-circuit with voltage-reapplication, MERSEN's has launched FE2E (Fuse Econom and Ecologically Efficient). FE2E is a collaborative research project, sponsored by BPI-France as FUI after AAP (Call for Project) nr. 15, and involving besides MERSEN eight other academic or industrial partners.

At first, MERSEN Electrical Protection has decided to increase the facilities of the test lab at Saint-Bonnet de Mure, in France. Main equipment concerns a new bench consisting of 4 stacks of capacitors. Each one of these stacks can be coupled under 2 and 4 kV. The capacitance of a stack reaches 32 mF under 2 kV and 8 mF under 4 kV. Capacitor stacks can be arranged in parallel, giving up to 126 mF under 2 kV. The very interesting characteristic is that a stack of capacitors can be discharged at controlled time t1 by closing of a switch S1 and others stacks of capacitors can be discharged at controlled time t2 = t1 + Δt by closing of a switch S2 (Figs. 10 and 11).

In addition, MERSEN is also studying the material aspects of the protection by fuse, especially thesis are running about arc electric. The challenge is to understand how the energy of the electrical arc is transmitted to the surrounding medium (Figs. 12 and 13).

Also, MERSEN has collaboration with CEDRAT for inductance calculation of fuses, bus-bars and fuses integrated inside bus-bars (Fig. 14).

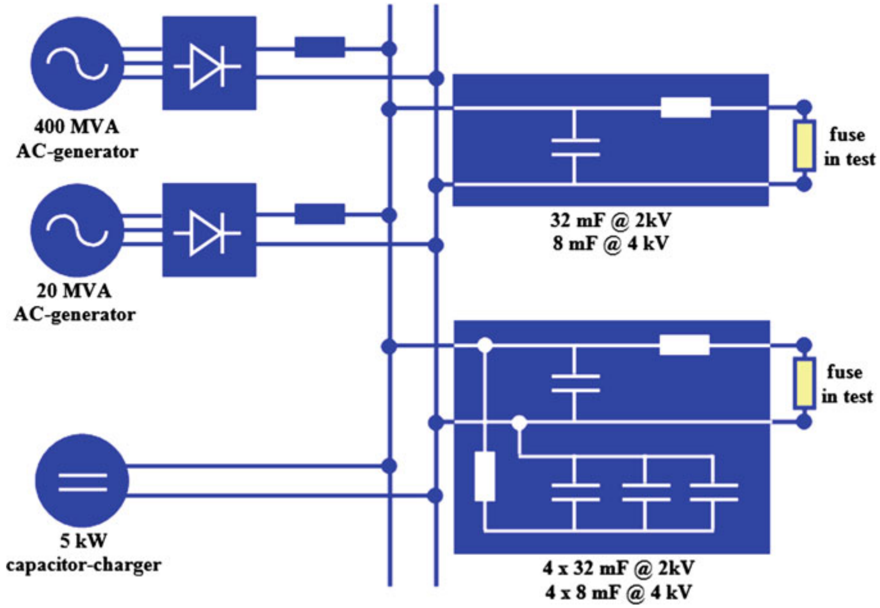


Fig. 10 Synopsis of the test facilities at MERSEN—Saint-Bonnet de Mure, in France

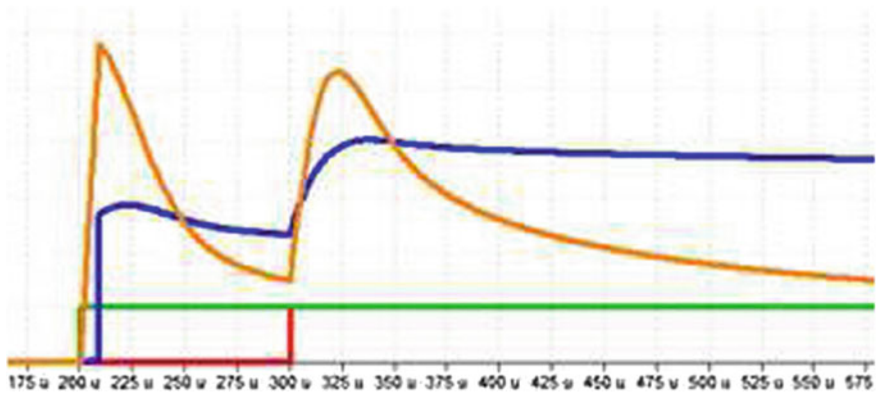


Fig. 11 State of S1 State of S2 Current in the fuse Voltage across the fuse

InCa3D is a soft-ware developed by CEDRAT in collaboration with G2Elab from Grenoble-INP. It is based on PEEC (Partial Equivalent Element Circuit)—method, in opposition to many soft-wares based on FEM (Finite Element Method). CEDRAT's engineers have implemented a new module for parasitic capacitances calculations. Another challenge is to integrate a coupling with thermal physic, major difficulty being that InCa3D uses PEEC-method with rectangular meshing and thermal solvers refer to FEM with tetrahedral meshing.

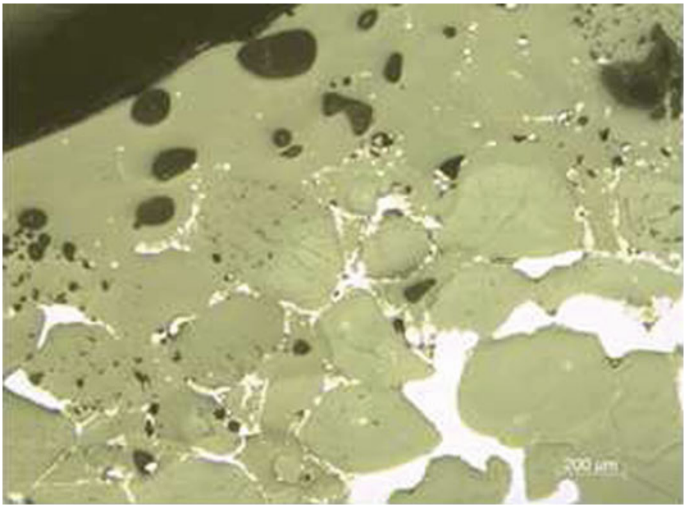


Fig. 12 Melted silica grains and re-condensed silver

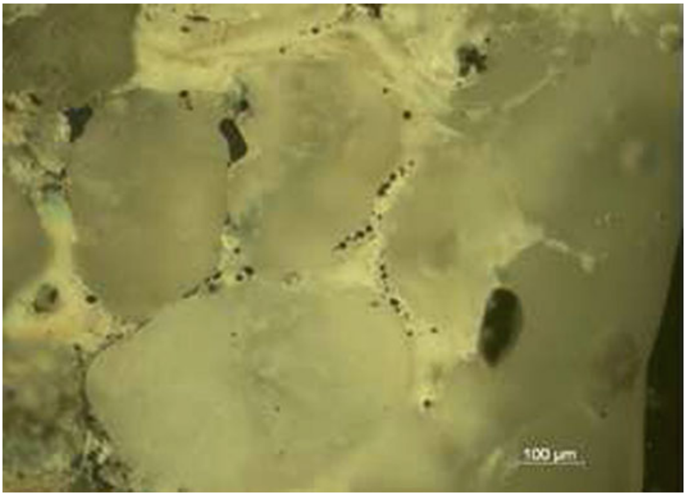


Fig. 13 Curls of melted silica pushed by vapor-pressure through not-melted grains

Also, calculation of electro-dynamical forces has been run, together with LAEPT at Clermont-Ferrand. These forces should explain decrease of prearcing I^2t of fuses under high di/dt as observed under some test-conditions. Another matter rises concerning the mechanical behavior of silver or copper under high deformation-speed and at high temperature. A specific study is carried out by LAMCOS from INSA-Lyon using Hopkinson's bench.

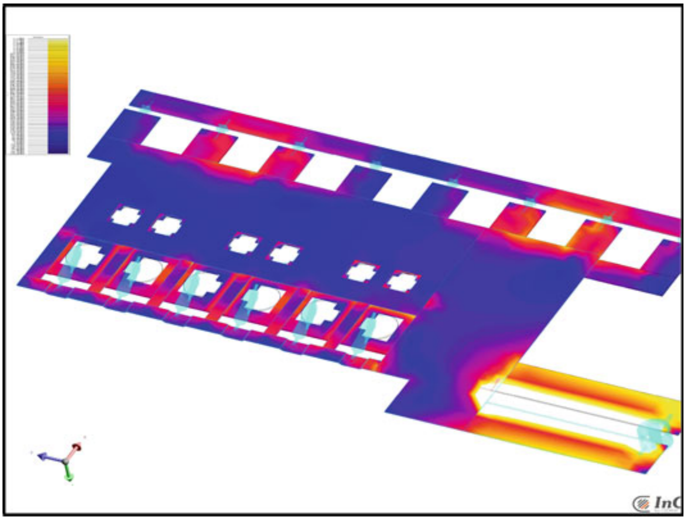


Fig. 14 Current distribution in a busbar

6 Conclusion

Since three decades, MERSEN has gained a lot of experience about the protection of inverters. A heavy knowledge is also available about the operation of a fuse, especially concerning the intimacy of arc versus granular medium and the inductance calculation of conductive elements. Because the energy of a capacitor is much lower than that can deliver a network through a transformer, it is expected that sizes of the fuses will be drastically shrunk, mainly in their length. That will reduce the value of the additional inductance due to the fuse and allow to solve a large quantity of cases of safety. As claims professor Stoke at ICEFA-Conference (International Conference on Electrical Fuses and their Applications) which was hold in Gdansk, in September 2003: "*Modern electric fuses are marvelous devices for protecting life and equipment from potential power of uncontrolled electricity. Since the coming of electricity in the 1870s, they have been in front line for electrical defense. Indeed, it is fair to say that without the virtually fail-safe protection of the electric fuse there would be no modern electrical industry. Electricity would be regarded as far too dangerous for widespread use*." Once again, that will be confirmed.

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Environmental Criteria for the Selection of Underground Transmission Cable Conductors

Frédéric Lesur, Amélie Lafragette, Agnès Labbaye and Aude Laurens

Abstract The results of major LCA studies show that under the assumption of European power mix, power losses dominate the cable impacts in nearly all categories, contributing with up to 96% to climate change for example. Therefore, it is relevant to focus primarily on the reduction of losses. Dealing with underground cable systems, it is essential to properly select the conductor for the expected service in the grid, because the metal core determines the amount of losses during the lifespan of the power link. Based on the scenario of a typical French underground circuit, the paper presents the calculations of cable losses, and illustrates a method to assess the optimal economic conductor taking into account the entire life span of the system, leading also to the best environmental solution with minimised losses. The French TSO has been developing models and methodology over the last decade in order to perform LCA on transmission systems. Leading the Cigré Working Group B1.36 [8], RTE has contributed to establish in 2015 a methodology dedicated to LCA for underground cables. In addition, a case study was carried out. This significant work allows the transmission system operators to identify the main environmental impacts of underground cables, their sources, as well as improvement targets. Electricity losses are identified as responsible for the main impacts (climate change for instance), while the extraction and the manufacturing phase of the metal components represent the outlines of mineral depletion impact. To overcome those environmental issues, different alternatives have to be compared, both to reduce losses and the mineral depletion. The study field needs to be extended to a more global scope, in order to integrate the whole benefits of the grid.

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The authors review and discuss their approach, results and works in progress within their company, with a common aim of the improvement of energy efficiency.

Keywords Underground cable systems · Aluminium · Copper · Conductor size · Design criteria · Current rating calculation · Losses · Global cost · Life cycle assessment · European platform on LCA · Environmental impact · Climate change · Energy policies · Metal depletion

1 Introduction

The selection of a conductor to transmit power through an underground cable system is linked to many criteria: electrical considerations, thermal design, installation techniques, mechanical stresses, etc. Obviously complying with an attractive economically tender… The environmental impact is increasingly taken into account, at the earlier stage of the cable design. Even if a comprehensive study of Life Cycle Assessment (LCA) is not available for a given global cable system, it is interesting for the cable engineer to start considering environmental criteria for the conductor who provides the function of current carrying.

The results of a renowned LCA study [1] show that under the assumption of European power mix, power losses dominate the cable impacts in nearly all categories, contributing with up to 96% to climate change for example. Therefore it is essential to properly select the conductor for the expected service in the grid, because the metal core determines the amount of losses during the lifespan of the power link.

2 Electrical Resistance of Conductors

The losses are proportional to the conductor resistance and to the square of current rating $R.I^2$. Since they represent the major part of the environmental footprint, a special attention is paid to the conductors themselves. For underground cables, only two metals are operated: copper and aluminium Fig. 1.

A few variations such as enamelled wires of copper or oxidised wires of aluminium are preferred in alternative current (AC) conditions, in order to mitigate the skin and proximity effects of large cross-section conductors. The AA 1370 aluminium grade is chosen for its purity (at least 99.7% of pure aluminium) [2]. According to Table 1, a ratio equal to 1.64 between aluminium and copper electrical resistivities requires bigger conductors when aluminium is chosen.

The calculation of the maximum permissible current rating in the steady-state operation of a cable system is given by a series of standards published by the International Electrotechnical Commission. First, the direct current (DC) resistance R_0 at 20 °C of standardised conductors (up to 2500 mm^2) is given by [3]. Then, a

Fig. 1 Extruded XLPE cables with aluminium and copper Milliken (segmented) conductors

Table 1 Characteristics of copper and aluminium used for electrical applications

Characteristics		Copper	Aluminium	AC resistance R of the conductor at its operating temperature θ
Electrical resistivity at 20 °C	ρ (Ω/m)	$1.7241.10^{-8}$	$2.8264.10^{-8}$	
Temperature coefficient at 20 °C	α_{20} (K^{-1})	0.00393	0.00403	$R' = R_0[1 + \alpha_{20}(\theta - 20)]$ $R = R'[1 + y_s + y_p]$
Density	d (kg/m^3)	8980	2720	

basic correction is applied to take into account the effect of the temperature, to get the DC resistance R' at the operating conditions. The final value of the AC resistance R is obtained with analytic formulae to assimilate the y_s skin and y_p proximity nonlinear effects.

3 French Practice for Transmission Cable Systems

Réseau de Transport d'Electricité (RTE), the French transmission system operator (TSO), generally contracts with cable system suppliers every three years, plus spot markets. The trend to harmonise an optimised range of components is effective. The qualification of transition joints made it possible to connect new cables to existing systems, and cables of different sizes in order conductor sizes are rationalised, leading to security of supply easier stock control, better assets homogeneity, lighter studies and easier management of repair (Table 2).

Table 2 Present range (2014–2016) of conductor sizes (mm^2) for new cable systems on the French grid

Copper	630	800	1000	1200	1600	2000	2500
Aluminium	630	800	1000	1200	1600	2000	2500

Enamelled and oxidised copper conductors have been used for improved cable ratings since 2011 for 1600–2500 mm^2 conductors. The regular 1600 mm^2 copper size has even been discarded in 2014.

The cable rating is calculated below according to IEC 60287 standard [4] for each conductor and a typical French installation in (semi-)urban area: cables laid in PVC ducts embedded in concrete with a trefoil geometry. Note: the result highly depends on the conductors' position (depth and axial distance) and on the assumptions of the thermal conditions. More than the values themselves, the reader will be interested in the relative performance of the conductors (aluminium, copper, enamelled copper) (Figs. 2 and 3).

Plastic ducts are extensively used. Touching high-density polyethylene (HDPE, with excellent fault containment if the thickness is sufficient) are installed in narrow trenches in rural area. Thin PVC ducts embedded in concrete with spacers are preferred in urban area to prevent any risk of third-party aggression. In both cases, cables can be easily removed for repair or upgrading. Civil works are carried out once and for all, with very few disturbances and environmental impact to replace

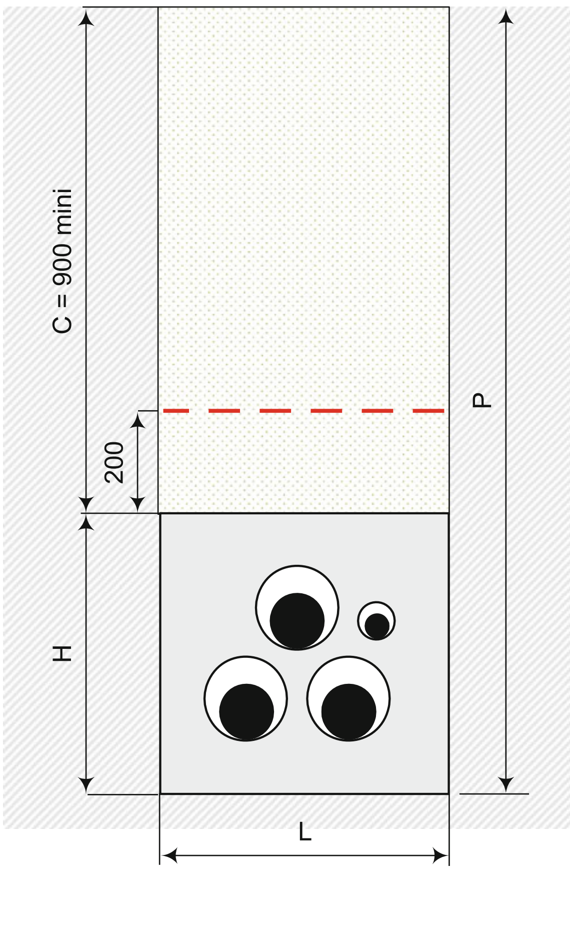


Fig. 2 225 kV XLPE circuit (ambient 13 + 5 °C, soil 0.85 K.m/W)

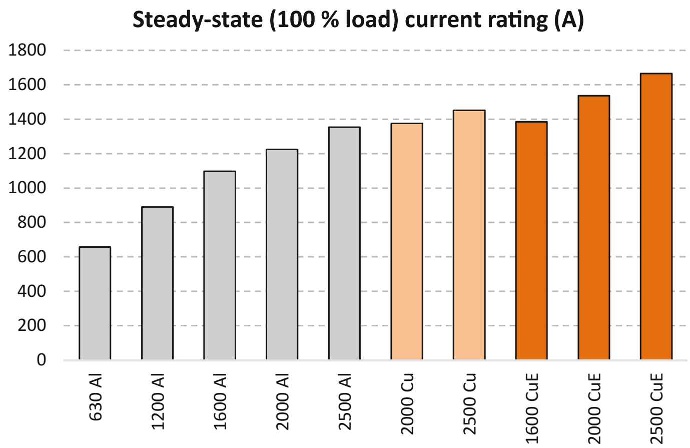


Fig. 3 Current ratings of present new conductors installed in France (according to configuration and thermal conditions of Fig. 2)

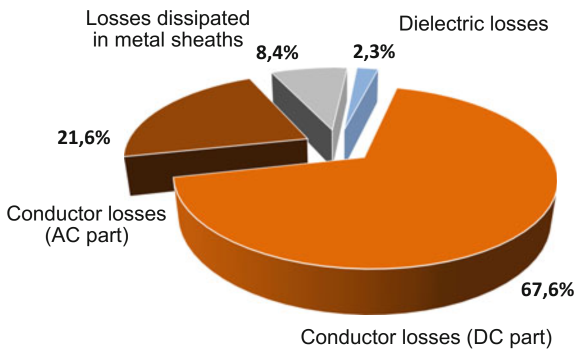
the cable system. This is also the guarantee to recover the cables at the end of life and to recycle the components. Contrary to overhead lines conductors, the ones of insulated cables are not oxidised by decades in free air. The material is therefore potentially highly valuable.

4 Losses Generated by Conductors

Cables generate dielectric losses in the insulation layer and induced losses in the metal screens and armours. The operation in DC mode saves these losses.

Figure 4 shows the distribution of the calculated losses for a 2000 mm^2 Cu cable system operated at the maximum current rating (1375 A) in the conditions specified by Fig. 2. Due to the significant axial distance between cables (ducts with spacer),

Fig. 4 Losses distribution of an AC cable system (2000 mm^2 Cu 225 kV)



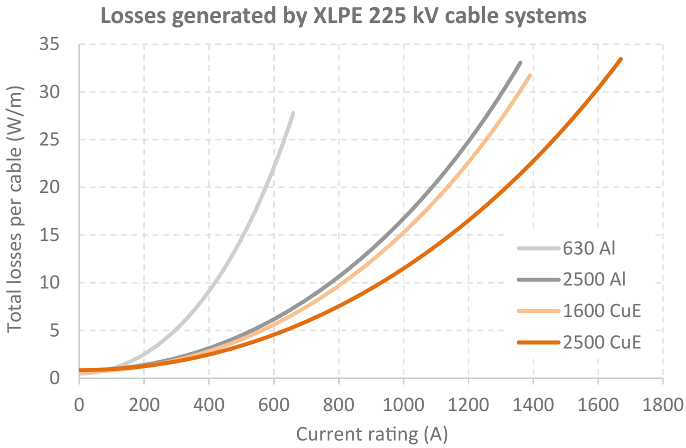


Fig. 5 Total losses dissipated per cable (W/m) (according to configuration and thermal conditions of Fig. 2)

the proximity effect y_p is linked to only 1% of the total losses versus 20.6% for the y_s skin effect. The assessment would be more balanced for touching cables.

Figure 5 shows the total losses for the cables recently installed in France (extreme values of the 630–2500 mm^2 aluminium and 1600–2500 mm^2 enamelled copper ranges) as a function of the current rating (A), in the conditions specified by Fig. 2. Curves end at the steady-state permissible current rating, leading to the maximum temperature of the insulation material (90 °C for XLPE = cross-linked polyethylene). The order of magnitude is 30 W/m per cable, and is reached well before for small (resistive) conductors.

RTE yearly statistics show that underground cables systems are operated more than 95% of the time at a current rating lower than 60% of the maximum rating. According to the parabolic $R.I^2$ shape of the curves, it means that the losses are well under their maximum value (approximately one third). The remaining 5% match with peak values and most constraining conditions (e.g. severe winter period with extensive use of electrical heating). An insulated cable is therefore operated in conditions leading to "acceptable" losses. This point is essential, considering that power losses dominate the cable environmental impact. The closer to the maximum point the cable is operated, the higher the environmental footprint and operation cost are.

5 Economical Design of Cable Conductors

The current rating of a cable system is assessed according its thermal behaviour. The cable is designed to withstand the maximum temperature of the insulating layer in any operation modes. Most of the time, the engineer opts for the closest conductor size allowing the required operating temperature, on the safe side within a wide range of standardised sizes. Up to now, this way of selection led to the minimal investment cost. However, the global cost of a power link depends also on the actualised cost of losses. A bigger conductor (more expensive at the purchasing date) may generate sufficiently lower losses than the thermally designed conductor to become significantly cheaper after a few decades, taking into account the cost of losses. This calculation is described in the IEC 60287-3-2 standard [5], leading to the proposal of the most cost-effective conductor size. The following example illustrates the methodology (Fig. 6).

Let us assume a scenario where the cable system has to transmit 700 A. Data are plotted on a graph as a function of the conductor size (two colours are used, respectively for aluminium and copper conductors): *CT* = *CI* + *CJ*, with the investment cost of the installed system (*CI*), the actualised cost of the losses (*CJ*) fitted to the specified current rating, and the total cost (*CT*).

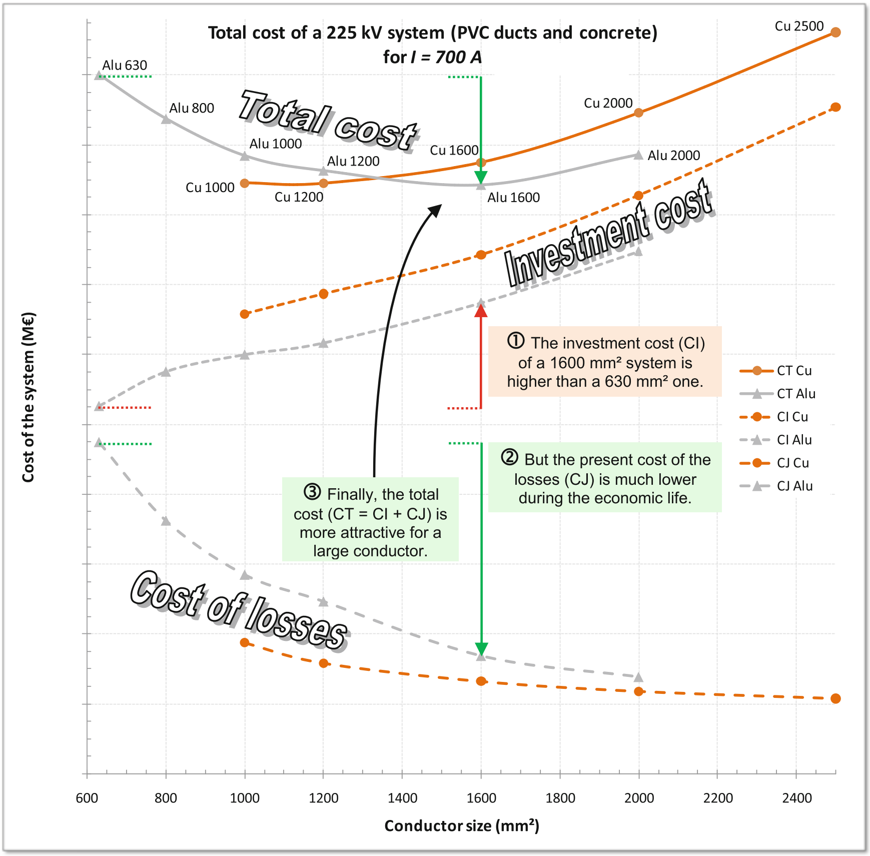


Fig. 6 Investment cost + actualised cost of losses = total cost during the economic life (according to configuration and thermal conditions of Fig. 2). (*Note* no data on the left axis, in order not to influence actual markets!)

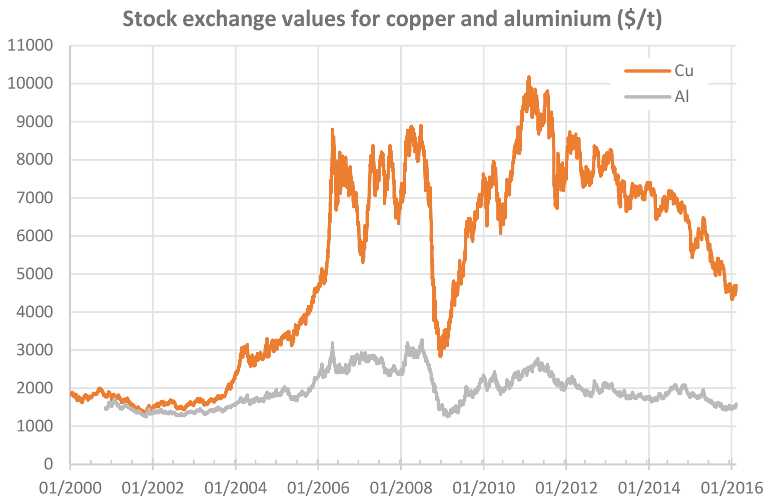


Fig. 7 London Metal Exchange values of conductor metals for the last past 16 years

The investment costs increases obviously with the conductor size (more metal), while the cost of losses decreases (less electric resistance). The combination of both trends leads to U-shaped curves with an optimal conductor size.

In the example, 1600 Al is the cheapest conductor to transmit 700 A during 50 years, according the considered scenario, while 630 Al would have been selected from a strict thermal design point of view (Fig. 7).

The engineer has to take into account the noticeable uncertainty linked to the input parameters, during the expected system economic life of several decades: price of Joule losses (€/W.h), annual increase of load (%), annual increase of cost of energy (%), annual discounting rate (%), etc. However the methodology is a useful prospective tool for decision-making.

The optimisation is not only of economic nature, but plays also a favourable role in terms of environmental impact. A Jicable paper [6] discusses the numerous additional technical advantages of such a policy: fewer losses and less risk of thermal ageing, limited risk of thermal runaway due to uncontrolled soil drying, larger safety margin to face load peaks or unexpected hot spots, margins for overloads, etc. Once again, fewer losses help in limiting global warming.

6 Prospects of Very Large Aluminium Conductors

While maximum standardised cross-sections of conductors moved from 1600 to 2500 mm^2 within the fifteen past years, some manufacturers offer today new solutions with aluminium conductors of 3000 or 4000 mm^2 (also found in Japanese former catalogues), pushing the present limits of copper conductors. RTE has performed a study to assess the interest of these huge components in terms of performance, installation, economics and environmental impact.

With reasonable assumptions, 3000 mm^2 Al could replace 2000 mm^2 Cu and 1600 mm^2 CuE, while 4000 mm^2 Al would be a substitute to 2500 Cu and 2000 mm^2 CuE, leading to approximately same maximum current ratings. For a given current rating, the cable with very large aluminium conductor generates less Joule losses than the associated cable with copper conductor.

The lower investment cost of the resulting aluminium cables would bring significant savings, despite the increased cost of installation (excavation, cable laying, assembly of joints, etc.). The engineer has then to balance the attractive global cost with identified additional constraints such as increased civil works, more rigid conductors and lower mechanical behaviour to tension pulling during the installation, increased size of drums or lower delivery length on site, which means shorter sections and more joints. A larger conductor diameter involves accessories of bigger size. It leads to increase the insulation capacity and the generated reactive power.

Finally, there is no experience in terms of qualification of such huge cable systems. Utilities and manufacturers have to collaborate to improve this topic.

7 Feedback from Environmental Studies on Underground Cable System and Issues

Life Cycle Assessment is the most complete environmental method to evaluate environmental impacts of a system. Based on the life cycle of an activity/system and on several environmental impacts, the methodology identifies the activity stages whose impacts are prevalent: while improving the required knowledge, relevant and feasible lever actions can be highlighted. When solutions are compared in order to select the best one in terms of environmental impacts, the LCA approach supports the decision (detecting potential transfer of pollution between alternatives for example).

LCA is promoted by the European Commission, which launched in 2005 the European Platform on LCA. Many data (in the ILCD handbook [7]) are available in the field of energy: electricity mix per country, fossil fuel chains, etc. They are used to implement the *Ecodesign directive* on the energy-using products. However, data on the electrical power system (and especially on its infrastructures) are quite limited for the moment.

LCA methodology for underground cable system includes different scopes:

- LCA on the waste management of cable material,
- LCA on the material for cables from cradle to gate of manufacturing site without the use phase by TSO of this system,
- LCA studies on underground power transmission line: manufacturing of the cable with the use phase by TSO: installation, maintenance, operation (power losses) and end of life.

Main results [8] show that the use phase (and especially power losses due to transmission activity) generates the most of environmental impacts (climate change, fossil depletion, fresh water eutrophication, acidification). The sensibility to the electricity mix has to be studied, due to its high influence. The metal depletion impact is mostly due to underground cable manufacturing.

The limits of the principle existing studies are relative to the fact that only a portion of the network (the project studied) is considered, and indeed is independent of the global system. The "classic" benefits of a network are not taken into account (pooling effect). Therefore the influence of the project (in particular on the dispatching modification) could be considered as negligible while they are not.

Most of the time, the power load is not considered. It means that congestion situations in the network are not taken into account whereas many infrastructure projects are required to solve them. Congestion reduction enables to use fewer thermal power plants responsible for the main greenhouse emission gas of the electric system.

Moving towards the energy transition raises two issues regarding the European energy policy. The energy transition involves more and more renewable energies. In order to give maximum value to these new power sources, the network needs some improvements (and sometimes reinforcement) to connect new areas of power generation to consumers with evolving habits. As the public calls into questions the needs of transmission infrastructure projects increasingly, it is really important for TSOs to be able to quantify and explain the contribution of their infrastructure projects to the fight against climate change.

For example, the new underground power link between France and Spain improves the access of the scheduled 30 GW of Spanish renewable energy to the European market. This interconnection increases the value of renewable energy for the community, while 1 million tCO_2eq can be saved every year [9].

Sharing the environmental challenges is not only a factor of better acceptance, but also a real stake to match the expectations for a new model of society.

TSOs and cable manufacturers shall work in close collaboration in order to improve those LCA studies (data collection, hypothesis for the life cycle inventory, identification and comparison of alternatives…), leading to the best solution for a sustainable business.

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HiDry^{72}: The Oil-Free and Safe Power Transformer for Sub-transmission Level

Mariano Berrogaín, Rafael Murillo and Joel Kern

Abstract HiDry^{72} is the safe and environmentally friendly solution in transformer technology for distribution and sub-transmission lines capable of reaching up to 63 MVA and 72.5 kV insulation level. The HiDry^{72} uses dry-type (non-oil) insulation materials to achieve these ratings. For the customer, this means superior safety and environmental friendliness for people and property. These advantages make the HiDry^{72} a product very suitable for applications in urban substations, power generation plants, substations located near or in public buildings or sensitive ecosystems, in cavern/underground locations and in crowded public places. This technology also provides the ability to install higher voltage systems directly to the main load centers; providing higher power and reducing distribution losses by reducing the amount of low voltage cable runs. The development of a dry-type power transformer for the 72.5 kV voltage class was already presented in 2011 [1]. Since then, a great interest has been shown in the market for many utilities as well as industries because all benefits inherent to the dry technology. In this abstract we report about the technology and some current projects in operation.

Keywords Dry-type power transformer · Subtransmission · Indoor substation · GIS · Fire-safety

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1 Introduction

In the past, the use of dry-type transformers was only possible in the distribution grid since there were no products available for voltages >36 kV. Dry-type power transformers for the 52 kV voltage class were introduced about a decade ago. They are meanwhile used in a number of utility and industrial installations and have proven their high reliability. The next level in voltage has recently been achieved when ABB introduced the HiDry^{72} transformers. These are dry-type power transformers for the 72,5 kV subtransmission voltage level. CIGRE already published in 2013 the brochure "Guide for transformer fire-safety practices" applying to power transformers rated >10 MVA and 66 kV [2]. A survey on transformer failures concluded that, assuming 50 years lifetime, one out of 20 transformers catches fire during its life.

HiDry^{72}, the dry-type power transformer for the 72.5 kV subtransmission voltage level, offers all general features of dry-type transformers. The major benefit being the lack of flammable liquids, as used in oil-filled power transformers. The dry-type transformer is non-explosive and self-extinguishing. In case of an external fire, its combustible mass is much smaller and much less smoke is created. Their installation and application is simple and fast. They have high strength against short-circuit or other mechanical loads and require less maintenance.

With the above advantages, the HiDry^{72} is therefore ideally suited for inner-city and underground installations. It can be installed in any building. When combined with GIT switchgear equipment, it will allow for future, simpler and compact substation designs [3].

The availability of an oil-free (dry-type) on-load tap changer has supported the introduction of the HiDry^{72} transformer product in the market. The first installations of HiDry^{72} transformer were presented at CIRED 2013 [4].

One important aspect to consider is the EcoDesign required by the European Union that has finally concluded in the EN50629 "Energy performance of large power transformers", $U_m > 36$ kV or $S_r > 40$ MVA. It is the first time there is an international requirement about efficiency in dry-type power transformers, and the HiDry^{72} transformers fulfill the requirements indeed.

2 HiDry^{72} Dry-Type Power Transformer Technology

The base for the development of the 72.5 kV dry power transformers were the well-established ABB medium voltage transformers in VCC technology; however, the higher voltage level, a higher rated power, and an increased range for voltage regulation lead to several technical challenges. An excellent understanding of the underlying physics and intensive use of FEM based simulations in combination with experimental testing were required for materializing a reliable new product [5].

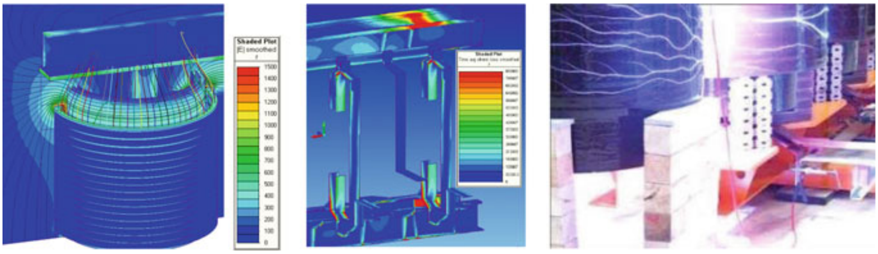

Fig. 1 Development of 72.5 kV dry-type power transformer: electric field simulation with electric stream lines, stray losses in structural components and busbars, and testing beyond the limits

The dielectric stress within a dry-type transformer is withstood by solid and air insulation. Due to the higher permittivity of the solid insulation, the electric field in the solid material is reduced and air becomes the main insulator. The dielectric strength of air is therefore the limiting factor and defines maximum electric fields and minimum insulation distances.

Magnetic stray fields can cause eddy currents in the windings which can become very significant with increased power rating and growing cross section of the conductors. The larger stray fields also create additional eddy losses and hot spots at unexpected locations. These eddy losses strongly depend on the winding design. When the OLTC is connected at its minimum position and part of the winding turns are "deactivated", the magnetic stray fields and eddy currents are especially strong and local hot spots can easily be generated (Fig. 1).

Although there is no IEC/ANSI standards for this product, HiDry72 fulfils the same partial discharge level as the standard requires for transformers up to 36 kV, (maximum 10 pC at 1.3 U_n). This guarantees that no degradation of the insulation due to PD is taking place and that the transformer will have a long lifetime.

3 HiDry72 Technical Features

The HiDry72 transformers offer identical functionality as 72.5 kV liquid-immersed power transformers [6]. The key characteristics are shown in Table 1.

3.1 Ageing and Overloading of Dry-Type Power Transformers

Both oil filled and dry-type transformer technologies have industry standard loading guides to help estimate overloading capabilities. Oil power transformers follow the loading guide IEC 60076-7 and the HiDry72 follows the one for dry-type transformers (IEC 60076-12, or IEE C57.96™). All of these standards show how the

Table 1 Characteristics of 72.5 kV dry-type power transformer HiDry[72]

Rated power	Up to 63 MVA	Partial discharge	<10 pC
Primary voltage	Up to 72.5 kV	Insulation class	F (155 °C) or H (180 °C)
Lightning impulse voltage	325 kV for IEC 350 kV for ANSI/IEEE	Environmental class	E2
Short duration AC withstand voltage	140 kV for IEC 140 kV for ANSI/IEEE	Climatic class	C2
Secondary voltage	Up to 36 kV	Fire class	F1
Connection group	Y or D	Cooling	AN, ANAF, AFAF, AFWF
Tapings	17 positions, $\pm 8 \times 1.25\%$	Enclosure	IP00 (none), IP21 (indoor) to IPX4D (outdoor)

operational conditions (loading profile, ambient temperature, etc.) and design characteristics (average temperature rise in windings…) can affect the overloads admitted and the lifetime of the transformer. They also indicate how measuring the insulation material ageing ratio as well as the calculation of loss of life, and therefore life expectancy, can be estimated in both technologies. What these standards detail is that each transformer has individualized overload capability curves that will depend on its own design (mass of conductors and mass of solid insulation). This method of ageing and overloading prediction is more advanced than the former loading guide that established curves solely depending on ambient temperature.

For lifetime ageing considerations, both transformer technologies (oil or dry-type) must be designed to operate continuously fora minimum of 180,000 h (20 years) working in nominal conditions (at full ratings). Therefore, from performance point of view, both technologies have the same life expectancy working in the same conditions.

The real lifetime for power transformers (oil and dry) can be much longer, however, in cases where the normal operation conditions are less than the full nameplate rated values, in time and loading. For example, the standards show that for dry-type transformers, an increase of 6 K in thermal rise doubles the ageing rate while a reduction of 6 K halves ageing rate. Furthermore, there is an additional margin coming from the gap between the measured values and the guaranteed limits regarding average temperature rise of the windings and core.

3.2 HiDry[72] Dry-Type Power Transformers Installations

A number of HiDry transformer indoor and outdoor substation installations have been carried out and are currently in operation. In the following section we present a few of these case examples:

1. Indoor 66 kV Substation in Industrial Plant

The ABB factory in Córdoba (Spain) has a long tradition of manufacturing transformers being since 1999 the ABB center of Excellence for shell-type transformers.

For both technical and safety reasons, it was decided in 2011 to upgrade the entire electrical installation of the factory (HV, MV and LV), in a turnkey project. The project included a complete substation with GIS, transformers, cells, lines, etc. And the two HiDry^{72} transformers manufactured by ABB in Zaragoza were installed (Fig. 2). Each one 12 MVA, 66/20 kV power rated, provided with an on-load dry tap changer (OLTC), with 17 positions and 1.25% tapping step, which will work as back-up on each.

2. Indoor 69 kV Substation in Soccer Stadium

This project in Salvador de Bahía (Brazil), where the new Fonte Nova Stadium hosted matches of the FIFA World Cup™ in 2014. This new building includes a new substation where two vacuum cast coil dry-type distribution transformers have been located: 2 × 25 MVA power rated, 69 kV at primary voltage, suitable for two levels of secondary voltage: 11.95 and 13.8 kV, and also provided with an on-load tap changer regulation OLTC (+4/−12) × 1.25%. Its main function is the power supply of the stadium as well as inner-city substation.

In fact, these two HiDry^{72} transformers have been installed under the access-stairs to the stadium (Fig. 3). The end user, which belongs to Coelba—Neoenergía Group, part of Iberdrola, showed special interest in ABB solutions for high power and large voltage transformers Fig. 3 shows that the transformer is installed without an enclosure. Instead a simple fence is used to prevent unintentional contact of service personal or other people with the energized transformer.

3. Outdoor 52 kV Substation in Forest

HiDry transformers are also used in outdoor installations in Sweden. The utility Ulricehamns Energi has installed a 16 MVA, 45/11 kV HiDry transformer in an outdoor substation (Fig. 4). The substation is located in an environmentally

Fig. 2 Installation of HiDry^{72} (12 MVA) in the bay (*left*). GIS installation (*right*)

Fig. 3 Fontenova stadium overall view (*left*). HiDry^{72} (25 MVA) and OLTC installation (*right*)

Fig. 4 Enclosure for outdoors (*left*). Unloading of HiDry^{72}(16 MVA) with the enclosure (*right*)

sensitive area and it is equipped with an OLTC (also oil-free) with voltage steps of $\pm 7 \times 1.67\%$. The transformer was delivered and installed in the enclosure (IPX4D) and with the OLTC mounted on the transformer (Fig. 4).

4. Outdoor 69 kV Substation for Gas combined cycle PP

Another oil-free power transformer is in the **US** where Wildcat Point will be one of the cleanest natural gas facilities of its size in Maryland (belonging to Old Dominium) and will generate approximately 1000 MW. The customer needed two

Fig. 5 Overallview of the power plant (*left*). HiDry^{72} (2 MVA) for outdoors during FAT (*right*)

HiDry^{72} transformers (2 × 2000 kVA, 67/6.9 kV NLTC for outdoors installation (enclosure NEMA 3R)) to feed a new pump station for cooling the power plant, in an environmentally sensitive area, since the substation is by the river (Fig. 5).

4 Indoor 66 KV Urban Substation

The latest installation is located in **Spain**, where Enel-Endesa has chosen the HiDry^{72} transformers for safety reasons. They chose the Hi Dry72 technology because the 4 transformers are in urban substations in the downtown of Sevillecity, close to livings and hospital (Fig. 6).

Figure 7 shows one of the four units 34 MVA 66/22 kV, including also OLTC (± 8 × 125%), YNyn0, installed in the substations and subject of dimensional restrictions of the substation. One of these transformers was short-circuited tested in CESI (2014) passing the test at first, showing an excellent reliability of the product (Fig. 7).

Fig. 6 Pictures nearby Arjona substation, in the downtown of Seville (Spain)

Fig. 7 HiDry^{72} (34 MVA) installed in the substation (*left*). One of the units 34 MVA was withstand short-circuit tested in CESI (Milan, 2014)

By choosing HiDry^{72} ABB provides a solution with a **superior safety for people and environment**, almost maintenance-free and with a very easy installation

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An MgB_2 HVDC Superconducting Cable for Power Transmission with a Reduced Carbon Footprint

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Abstract Superconducting power cables represent a recent innovative development for high-capacity underground transmission. They are set to join the portfolio of technologies that will be needed to accommodate the growing demands on electricity grids. These demands are brought about in particular by the rising amount of renewable energy and the increase in decentralized power generation. The promise of superconducting electric cables lies principally in their small size, with potential advantages in terms of environmental impact, efficiency and public acceptance.

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The advantages of superconductivity have been acknowledged by the European Commission with its funding of BEST PATHS (an acronym for “BEyond State-of-the-art Technologies for rePowering Ac corridors and multi-Terminal HVDC Systems”), a collaborative project on energy transmission that includes a superconducting power transmission line as one of its five constituent demonstrators. Coordinated by leading cable manufacturer Nexans, the superconducting demonstrator brings together transmission system operators, industry, and research organizations with the aim of validating the MgB_2 technology for power transfer higher than 3 GW. In order to investigate the technological maturity of superconducting HVDC links, a monopole cable system based on MgB_2 wires and operating in helium gas at 10 kA and 320 kV will be developed and tested in accordance with international practices. In addition to the design, development, optimization, manufacturing and testing activities, special attention will be devoted to studying the integration of a superconducting link into the future transmission grid and to assessing the availability and economic viability of the system. An overview of the project will be presented at the conference, including the main tasks and challenges ahead as well as preliminary results after the first year of activity.

Keywords BEST PATHS · High-power transmission lines · HVDC · MgB_2 cables · Superconducting links

1 Introduction

One of the main outcomes of the recently concluded EU FP7 e-Highway 2050 project [1] was the identification of the ‘electricity highways’ required in 2050 in order to facilitate investment decisions in the coming years. Five scenarios were

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selected to comprise a wide range of possibilities in 2050 with regard to relevant criteria and were based on the common target of reducing CO_2 emissions by 95%. The results highlighted the importance of bulk power links with lengths of hundreds of kilometers, and several additional power transmission corridors with capacities from 5 to 20 GW were explicitly identified for the European grid. In particular, major North-South corridors and connections of peninsulas and islands to continental Europe were shown to be critical.

Despite having been ready for deployment in energy-related applications for some years now, superconductors are yet to be utilized for very long stretches and still need to be validated for DC system operation. The conventional solutions presently used for power transmission in the range of 1–8 GW include overhead lines, underground cables with extruded insulation (XLPE), and gas-insulated lines (GIL). They usually require large right-of-way corridors and/or extensive civil engineering. By contrast, the compactness of superconducting cables means that they need narrow corridors and reasonable trenches, which results in a reduced environmental footprint. Furthermore, superconducting links do not suffer from the same limitations in terms of transmitted power and length characteristic of existing buried links.

In this context, the main goal of the DEMO 5 demonstrator within the BEST PATHS European project is to investigate the technological maturity of superconducting HVDC links for operation in the grid. This demonstrator will also be a first attempt to employ MgB_2 as a superconductor for HVDC cables. Due to the low cost and high transport current of the MgB_2 wires at the low magnetic fields of interest for energy transfer applications, these cables are expected to be competitive with conventional resistive XLPE cables.

2 Project Description Including Main Challenges

DEMO 5 aims to develop an HVDC monopole superconducting cable designed to operate at 10 kA and 320 kV, corresponding to a transferred power of up to 3.2 GW [2]. The high-current capability of the MgB_2 superconductor was already demonstrated at CERN in 2014, when two 20-meter-long MgB_2 cable assemblies were successfully operated in DC mode at 20 kA at 24 K [3]. The high-voltage tests of the superconducting system will be carried out at the Nexans high-voltage cryogenics platform in Hanover based on the CIGRÉ recommendation B1.31 [4] and in accordance with current standards for conventional DC cables.

The superconducting wires used for the high-current cable will be produced by Columbus Superconductors through the Powder-in-Tube ex situ process [5], which recently led to the design and fabrication of round MgB_2 wires in kilometer lengths. The preliminary wire is a monel-nickel sheathed wire with a diameter of about 1.3 mm containing 36–37 MgB_2 filaments with a filling factor of 13–16% of the total surface. In order to ensure the transfer of more than 10 kA at 20 K while maintaining a compact design, the cable conductor will consist of 18–36 round

MgB_2 wires twisted around a flexible multi-strand copper core. The external diameter of such a conductor is 9–17 mm.

A cryogenic cooling system that allows the cable to operate in helium gas in the range of 15–25 K and at 20 bar will be developed as part of the demonstration activity. Thus, the cryogenic envelope will consist of multiple concentric tubes. Firstly, the conductor will be inserted into the inner helium-cooled cryostat whose outer wall is lapped in high-voltage insulation. Secondly, the inner cryostat is housed in an outer flexible cryogenic envelope, which is cooled by liquid nitrogen acting as a thermal shield. This helps keep thermal losses at an acceptable level. The insulating tapes will therefore be impregnated with liquid nitrogen in the fashion currently employed for oil-impregnated conventional cables. The material foreseen for the electrical insulation is polypropylene laminated paper (PPLP) tape.

As a certain degree of flexibility is needed for the cable installation, corrugated tubes will be used for the cryogenic envelope. Such tubes are routinely manufactured in hectometer lengths, delivered on drums and can be joined on site for multi-kilometer-long systems. Appropriate cooling machines that are optimized for this type of application are already commercially available. For the demonstrator, a refrigerator capable of delivering 120 W at 20 K and circulating gaseous helium at 20 bar is under procurement. It should be noted that the overall required cooling power is determined mostly by the current leads and by the cryostat thermal leak from room temperature, since the AC losses of a DC system are greatly reduced when compared to an AC cable.

In contrast to the cryostats and the refrigeration system, mainstream solutions are not available for testing the HV insulation performance for operation in DC mode. Instead, a dedicated experimental setup will be developed for this purpose by ESPCI ParisTech. Measurements [6] will be conducted while the cable is under high electric stress of up to 60 kV in liquid nitrogen at a pressure of 5 bar and at variable temperatures. Given these harsh environmental conditions, the new test station should not only validate the insulation structure of the proposed BEST PATHS cable, but could also open the door for new cable structures and insulation studies.

Innovative solutions are also needed for designing and optimizing the cryogenic electrical terminations, since this will be the first instance where a flow of cold helium gas at 20 bar is injected at HV in association with high current. The heat inleak at 20 K should be as low as possible for a cost-competitive and robust concept. Thus, the proposed design will include a hybrid current lead for the current injection, and a special insulated line for the helium gas injection. The latter will be installed in parallel to the current lead and will connect the electrically grounded cooling machine to the cable conductor at 320 kV of electrical potential.

The simulation task in the project will be carried out by several partners led by KIT and is dedicated to analyzing the electromagnetic behavior of the MgB_2 cable conductor, especially with respect to transient events. To this end, a numerical model that solves the time-dependent Maxwell's equations by using the finite-element method will be employed [7]. The model is able to reproduce the precise geometry of the MgB_2 wire at the level of the individual filaments and incorporates highly non-linear characteristics of the materials from which the cable is made.

The reliability and availability of the system are of key importance for its acceptance by transmission system operators. Therefore during the second half of the project, specific vision studies for very long systems (>100 km) will be conducted to investigate the future technologies for the cryo-envelope and for possible cooling systems operating with gaseous helium or liquid hydrogen. The level of system availability is dependent on the cooling power and on the redundancy of the cryogenic fluid management systems, which can have a significant impact on the investment costs for the system. Moreover, minimizing the number of cooling stations is essential for an efficient operation over very long distances and for decreasing the investment costs.

These results will be used for an economic viability analysis of the proposed superconducting HVDC cable solution, taking into account not only the cost of the cable itself, but also estimated costs for the substations and civil engineering. The socio-economic assessment will also include a comparison with resistive cables and with solutions based on high-temperature superconductors for relevant case studies.

3 First Assessment of the Environmental Impact of MgB_2 Superconducting Cables

In what follows, the potential environmental impact of the MgB_2 superconducting cable system is presented in a preliminary fashion using the Life Cycle Assessment (LCA) methodology based on the ISO 14040-44 standard series [8, 9]. The cable under study is made out of MgB_2 superconducting core material and the installation comprises two cooling circuits in parallel. The functional unit considered for the LCA is "*transmitting an electric current of 10 kA over a distance of 1* km *for 40 years at a 100% use rate in accordance with the relevant standards*". The cable design used for this first assessment is shown in Fig. 1.

As a first step, the manufacturing of the cable was investigated based on MgB_2 wire data provided by Columbus Superconductors and on dielectric and cryostat data derived from high-temperature superconducting systems that were designed by Nexans. At this stage, the energy consumption for the manufacturing processes was not taken into account due to lack of data. Nevertheless, this is not expected to make a tangible contribution.

Figure 2 illustrates the relative environmental impact of the manufacturing of each cable component across a range of common indicators. The outer and inner cryostats appear to have the dominant impact with regard to global warming potential, cumulative energy demand, and water withdrawal. Moreover, the MgB_2 wires appear to impact the depletion of abiotic resources (raw materials) the most.

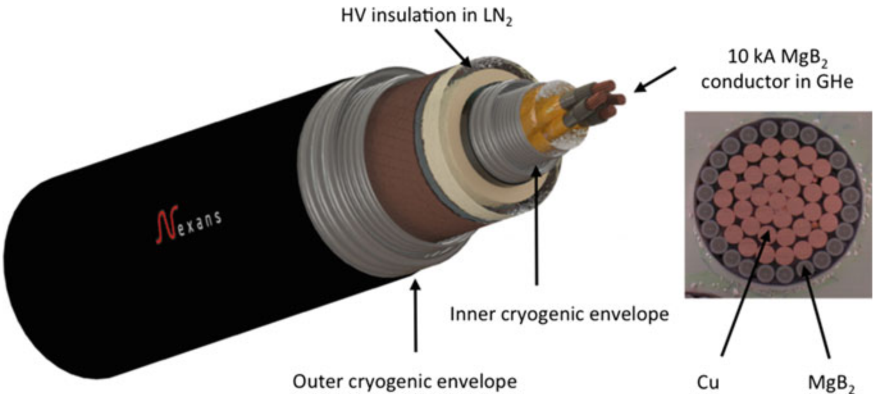

Fig. 1 The HVDC cable design for a 3 GW power link based on the MgB_2 superconductor

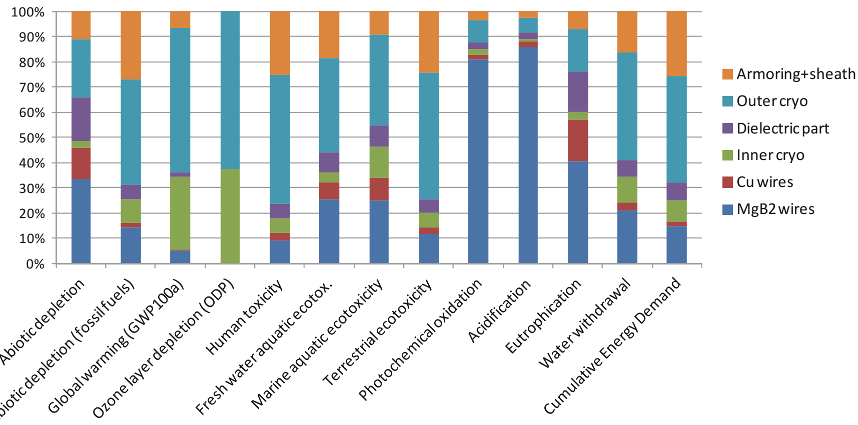

Fig. 2 Relative impact of manufacturing stage for an MgB_2 superconducting cable

More precise modeling of the system will be carried out over the duration of the project. Besides including the manufacturing energy consumption, the next steps will encompass the assessment of the use stage, the analysis of the complete system including joints and terminations, and a comparison with HVDC conventional cable systems.

LCA studies of standard resistive cables identified electricity losses as the primary cause of environmental impact. For instance, it was shown that under the assumption of the current European power mix, power losses dominate the impact of cables in nearly all categories, accounting for up to 99% of their global warming contribution [10]. To amend this, an effort must be made in the initial design phase to minimize electrical resistance. Moreover, the mutual heating effects among the cables of a circuit and between adjacent circuits increase losses (about 30 W/m per cable at full load) and lower the power rating. A target of 5 GVA can be achieved with a minimum of four parallel extruded cable bipoles (up to 2500 mm^2 copper at ±320 kV). However, their installation requires a large amount of raw materials and significant excavation work, along with increased traffic at the site during installation. In order to supply more power, the axial distances between cables and between circuits have to be increased, resulting in a larger right of way. Due to this, current development efforts are focused on bringing the thermal losses of superconducting cables to an acceptable level when compared to the Joule losses of resistive cables. If this challenge can be met, the compactness of the MgB_2 solution holds real potential as a design with a low global environmental impact.

4 Conclusions

As part of the BEST PATHS European project, DEMO 5 is a demonstrator project dedicated to superconducting electric lines, which aims to validate the novel MgB_2 technology for GW-level HVDC power transmission. The research and development work carried out in the first year of activities will continue throughout 2016, while the assembly and finalizing of the demonstrator installation will take place in 2017, and testing will begin in 2018.

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Part IV
Materials, Substances

g^3—The Alternative to SF_6 for High-Voltage Equipment

Elodie Laruelle, Yannick Kieffel and Arnaud Ficheux

Abstract Since the 1970s, transmission and distribution network relies on SF_6 technology because of its remarkable arc quenching properties and dielectric insulation. However, with its high GWP of 23,500 and an atmospheric lifetime of 3200 years, the SF_6 insulating gas has significant environmental impacts if it leaks into the atmosphere. In a first part, the paper draws up a status of the regulatory and financial constraints on SF_6 in the world. In a second part, the paper develops how Grid Solutions, a joint venture between GE and Alstom, has addressed this environmental issue, by developing, together with the 3M Company, a SF_6-free solution. The result is a gas mixture named g^3 (green gas for grid), based on 3M Novec^{TM} 4710 and CO_2. This new gas mixture reduces the global warming potential by 98% compared to SF_6 with only minor design modifications by respect to typical SF_6 design. It is a technically and economically viable alternative to SF_6, which let foresee a major revolution in the high-voltage technology. Finally, the paper describes the first applications of this g^3 mixture to 420 kV Gas-Insulated Lines (GIL). Indeed, at this voltage level, GIL represents on average 50% of the SF_6 installed mass in a global high voltage substation. SF_6-free GIL can thus bring a quick and massive reduction of SF_6 mass installed by utilities. The environmental benefits of this new technology is provided though the results of a complete Life Cycle Assessment (LCA) that has been carried out to compare SF_6 and g^3 technology. This LCA shows that the use of g^3 in the 420 kV GIL allows to considerably reduce environmental impact on Global Warming but also on all other environmental indicators (ozone depletion, acidification, metal depletion, etc.), compared to the SF_6 technology.

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Keywords SF_6 · Regulations · Gas insulated switchgear · Gas insulated line · GIS · GIL · Alternative gases · Environmental impact · Carbon footprint · Eco-design

1 Introduction

Since the 1970s, transmission and distribution network relies on SF_6 technology because of its remarkable arc quenching properties and dielectric insulation.

Nevertheless, SF_6 has the major drawback of presenting a global warming potential (GWP) of 23,500 (relative to CO_2 over 100 years), and it has a lifetime in the atmosphere of 3,200 years. As a consequence, it is considered as one of the gases presenting the most potent greenhouse effect [1]. One kilogramme of SF_6 released into the atmosphere has therefore the equivalent global warming impact as 23.5 tons of CO_2.

In 1997, at the third Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC), 37 countries have committed themselves to a reduction of greenhouse gases (GHG) emissions of 5% from 1990 levels by the year 2012. This agreement subsequently became known as the Kyoto Protocol and listed 6 GHG for which emissions need to be limited, among them SF_6. Since this date, to comply with this target, policy makers are developing more and more regulations and taxes, which have led industry to seek alternatives to SF_6.

The target of this paper is to present how environmental pressure on SF_6 associated with company's clean grid programme has push Grid Solutions to development a viable alternative to SF_6 for high-voltage equipment.

2 State of the Regulatory and Financial Constraints on SF_6

To achieve its Kyoto target, the European Commission has adopted on 17 May 2006 the Regulation (EC) No 842/2006 on certain fluorinated greenhouse gases (commonly called F-Gas Regulation).

This Regulation lays down specific requirements for the different stages of the whole life cycle of F-Gases, including SF_6: from production to end of life. Thus, it affects producers, importers, exporters, manufacturers of products containing F-gases and operators of the equipment. This regulation has been replaced by Regulation (EC) No. 517/2014 that came into effect on 1st January 2015. Main obligations for high-voltage equipment containing SF_6 are the following:

- Prevention of emissions (Art.3)
- Obligation to check leakage detection systems (Art.5)
- Obligation to recover SF_6 (Art.8)

- Training and certification mandatory for personnel carrying out installation, servicing, maintenance, repair or decommissioning of electrical switchgear (Art.9)
- Labelling of products with SF_6 quantity and Global Warming Potential (Art.12)
- Reporting (Art.19).

This regulation do not imposes any taxes on SF6, but it was the first mandatory and constraining requirements for high-voltage switchgears.

Some European countries have decided to go further than F-gas regulation requirements, as illustrated on Fig. 1.

Switzerland, Denmark and Austria have put in place a general ban of SF_6, however, high voltage systems above 1 kV are exempted. A condition of this exemption is that no alternative to SF_6 exists for this category of products.

Others countries have implemented a carbon tax for SF_6, either on the use or on the emissions of SF_6. As an example, since 2001, Denmark has set up a tax of 53€/kg of SF_6 imported in the country. In Slovenia, the level of the tax depends on the purpose of the use of F-gases: the first filling of pre-charged equipment is taxed 5%, corresponding to 17€/kg of SF_6, while SF_6 quantities used for servicing and maintenance of equipment are taxed 100%, i.e. about 340€/kg of SF_6. In Spain, only SF_6 used for maintenance is taxed.

Regulation and taxes pressure do not come only from European Countries.

In US, in order to reduce SF_6 emissions, California and Massachusetts have implemented a maximum annual leakage rate for high-voltage switchgear with the obligation to recover SF_6 as well as reporting.

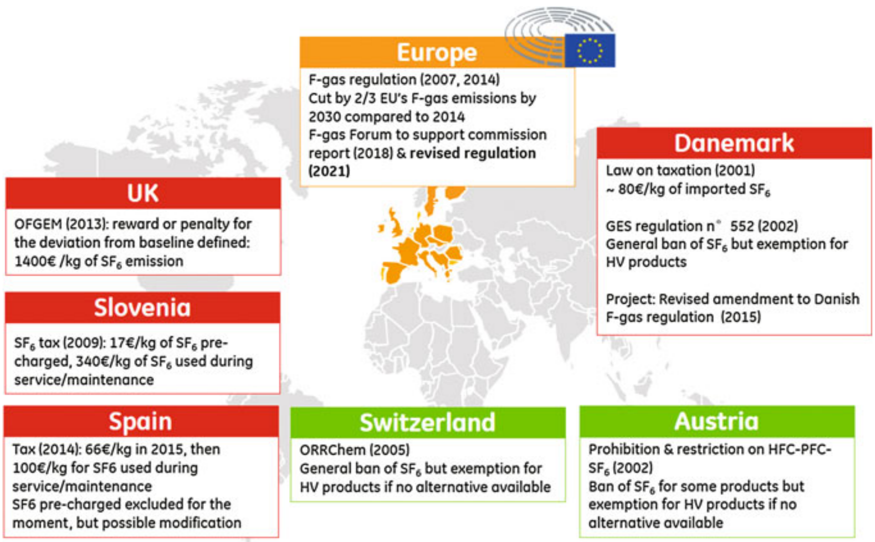

Fig. 1 Examples of SF_6 regulations and taxes in Europe

In Oceania, in 2011, Australia has caused a good deal of commotion by implementing the biggest SF_6 tax never seen before: about 400€/kg of SF_6 imported in the countries. The tax has finally been repealed due to a change of government, and is now only about 150€/ton of SF_6. New Zealand has also a carbon tax for SF_6 emissions, currently around 130€/kg SF_6 emitted.

Thus, a lot of countries in the world have implemented concrete measure to respect their commitment to reduce green-house gas emissions. This has resulted by an increase of regulations and taxes on gases having an impact on global warming. This tendency will only grow and continue in the next years since the Paris Agreement [2] has been signed by 195 nations worldwide at the COP21 conference in December 2015, bringing all nations into a common consensus on their current and future responsibilities regarding the use of carbon and addressing climate change.

3 Clean Grid Programme of GE's Grid Solutions

Since years, GE's Grid Solutions has been integrating the environment into the design of its products. For the specific gas-Insulated substations (GIS) applications, the eco-design approach is to reduce the global environmental impact over its whole life cycle, from the extraction of the raw materials until the end-of-life with due consideration of all environmental indicators.

SF_6 is obviously impacting the environmental performance of the GIS. The life-cycle assessment (LCA) performed on a GIS shows that SF_6 emissions can represent between 60 and 80% of the total Global Warming impact of the substation over its whole life. Used materials and power losses during the use phase have a high contribution on the other indicators.

Through its clean grid programme and in order to limit the SF_6 emissions, Grid Solutions has implemented several actions to monitor these aspects during the development of the GIS products. Reduction of SF_6 quantities and of seal length is carefully monitored through key performance indicators. Selection and validation of optimum technologies of gaskets [3] are key to ensure tightness during the lifetime of the equipment. Development of state-of-the-art monitoring system in GIS substations has facilitated early detection and prediction of any abnormal leakage. In order to limit any risk of SF_6 emission during site installation, the factory assembly of maximum of components is an optimum solution and it has been implemented during the past years on GIS from 72.5 kV up to now 420 kV [4].

These improvements in the design of GIS are beneficial to limit the emissions of SF_6 and proven experience in service gives full satisfaction to the utilities when dealing with SF_6 obligations like reporting.

One step further of the clean programme is to deal with replacement of SF_6, as detailed in next chapters.

4 Development of g^3 Mixture—A SF_6-free Solution

Aware of the environmental issue of SF_6, Grid Solutions has researched for four years an economical green SF_6 alternative solution for high-voltage switchgear. The objective was to find a gas that:

- meets all the very tough specifications for HV switchgear (high dielectric strength, good arc quenching capability, low boiling point, high heat dissipation, compatibility with existing switchgear materials, easy handling, design compactness, etc.)
- has a low global warming potential (GWP) and no impact on ozone depletion
- has a low toxicity (at least similar to SF_6 one).

When looking for alternatives available on the market, either the dielectric strength was too low (with negative consequences on dimensions and therefore on investment costs), either their GWP were still too high, either they did not meet health requirements.

Finally, Grid Solutions has developed an SF_6-free solution which meets all these needs. The solution is a gas mixture based on CO_2 and 3M Novec™ 4710 Dielectric Fluid from the fluoronitrile family. It was specially developed by 3M for that purpose and referred to by the name g^3 (green gas for grid) [5]. With a GWP of 327 compared to 23,500 for SF_6, g^3 reduces the global warming potential by 98% compared to SF_6 with only minor design modifications by respect to typical SF_6 design. It is a technically and economically viable alternative to SF_6, which lets foresee a major revolution in the high-voltage technology.

5 First Application of g^3 Mixture

The first application of this g^3 mixture is the 420 kV Gas-Insulated Lines (GIL). Indeed, at this voltage level, GIL represents on average 50% of the SF_6 installed mass in a global substation. SF_6-free GIL can thus bring a quick and massive reduction of SF_6 mass installed by utilities.

To give a practical example of the huge quantity of SF_6 that a GIL can contain, Fig. 2 illustrates the Jebel Ali M 420 kV GIL project in United Arab Emirates, energized in 2009. The cumulative one-phase length of this GIL is about 13 km. It contains 73 tons of SF_6, equivalent to more than 1700 tons of equivalent CO_2. With g^3 solution, this quantity would have been reduced by 98%.

Without any doubt, g^3 bring a considerable environmental benefit on climate change. In order to have a global view on the environmental impact on this solution over the whole life cycle of the product, a complete Life Cycle Assessment (LCA) has been carried out. It compares SF_6 and g^3 technology on all environmental indicators: global warming, but also ozone depletion, acidification, etc., considering the design adaptations needed until the end of life of the product [6].

Fig. 2 Jebel Ali M—United Arab Emirates

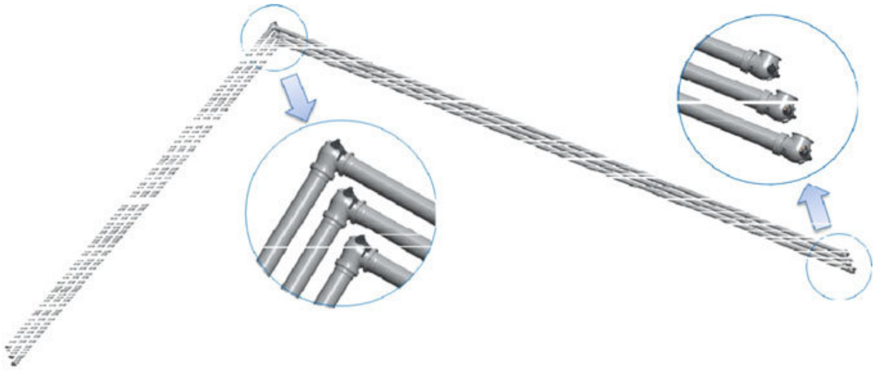

Fig. 3 Functional unit considered for the environmental study

The functional unit under study is one 100 m long section of 420 kV, 4000 A, T155 GIL, suitable for ambient temperature up to −25 °C with 2 direction changes, as presented on Fig. 3, and with the assumption of an operational life of 40 years.

The scope of the study can be summarised as followings:

- Raw material used
- Factory assembly
- Transportation from factory to customer site
- Use during 40 years, considering electrical losses, emissions in the air and during maintenance activities
- End-of-life with gas recovery, transportation and recycling of recyclable materials.

Table 1 Comparison of the SF_6 and g^3 420 kV GIL technologies

	T155 420 kV SF_6	T155 420 kV g^3	%
Total mass of the GIL (kg)	12,046	12,995	7.9
Gas quantity (kg SF_6—kg g^3)	1649	743	−55.0
Joule losses over 40 years	1242	1169	−5.9
Impact of gas losses over 40 years (t eq. CO_2)	7749	102	−98.7

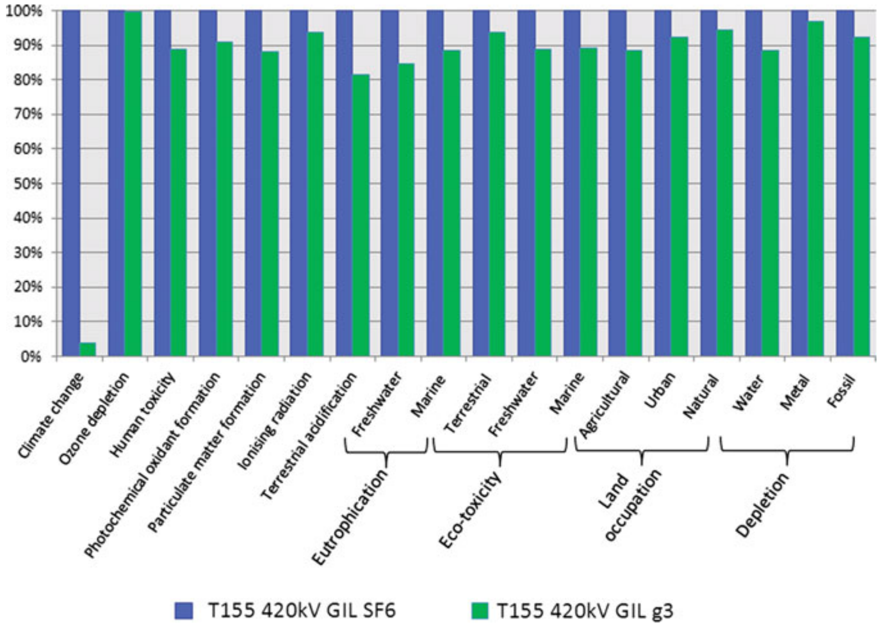

Fig. 4 Result of comparative LCA between SF_6 and g^3 GIL technology

The following Table 1 summarizes the various data of this environmental study.

Results of the environmental comparison are shown on Fig. 4. As normally performed for such study all environmental indicators have been considered. This is the only correct methodology to compare the environmental impact of two technologies from a global view, ensuring that no pollution transfer occurs.

The results of this LCA show that the use of g^3 in the 420 kV GIL is considerably reducing the environmental impact compared to the use of SF_6 technology. There is a huge reduction of 96% on Global Warming indicator and there is an average reduction of 14% on all other environmental indicators (ozone depletion, acidification, metal depletion, etc.).

6 Conclusion

During last ten years, regulatory pressure has been growing on SF_6 due to its high impact on global warming. Grid Solutions has a proactive policy to cope with these new challenges and to reduce impact of human activity on climate change. Grid Solutions has worked intensively to optimise the design of their GIS in that field and also to find an alternative solution to be used in its high-voltage equipment. g^3 represents the first economical green alternative to SF_6. Its GWP is 98% lower than SF_6 one, and its environmental benefits has been proven by a complete LCA performed on the 420 kV GIL. It will be the first g^3 product to be energised and that will happen in the UK mid of 2016. The availability of this new green gas alternative introduces the potential for a tremendous reduction in the tons of CO_2 equivalents deployed in this technology worldwide and is expected as a major breakthrough in high-voltage technology.

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SF_6 Management from Craddle to Craddle Advantage of SF_6 Recycling

Etienne Barbier

Abstract SF_6 is a very safe gas, which will continue to be used for years. Due to its hudge GWP SF_6 has to be mastered, recovered and retreated for reuse—Greenway, an eco label issued by Inventec helps to have a more responsible management of SF_6 i Recycling allows to drive the gas from cradle to cradle.

Keywords SF_6 recycling · Eco program · Substitution · Environmental approach

1 Introduction

INVENTEC company is an international company. Our main activity is the filling and the distribution of various gas and chemicals worldwide. We belong to the Dehon Group.

DIA 1 à 3

Since 1989, the Dehon Group took into consideration the risk posed by the non mastered management of used GHG. The Group developed a network of packing dedicated to the recovery of used gases, while his business at the time was to deliver full containers of virgin gas. This allowed for the first time installers to empty installations in managed and monitored packaging.

The recovery of used GES was not enough and the Dehon Group has developed a processing technology for used GHG in order to give them a second life and thus creating probably one of the first virtuous cycles of circular economy.

Thereafter, the Dehon Group was able to duplicate this French technology to other European countries. This process has evolved and has been adapted especially to SF_6 and to solvents. Foreshadowing the legal development including the reduction of CFCs, the Dehon Group, through INVENTEC for SF_6 activity anticipated very early the environmental issues, and structured a thinking around a sustainable recovery system. In 2002 Dehon Group has implemented for SF_6 a

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process of unique and innovative circular economy which was to make available to its consumer customers GHG returnable recovery packages that would be processed through recycling and regeneration unit.

The organization of recovery and recycling operations for fluorinated refrigerants really appeared three years later, through the signing of an agreement by the then Minister of Environment, Mrs. Ségolène Royal, the President of ADEME, and major producers and distributors of fluorinated gases.

1.1 DIA 4

SF_6 gas insures the security in the distribution of electricity.

It as a non toxic gas when it is brand new/non flammable and very safe for the workers.

This insulating gas is very efficient and is filled in numerous MV and HV breakers It is a safe gas for the workers. However its GWP is extremely high.

A lot of efforts have been paid in order to find alternative gases. The substitution of this gas is just starting and tests are done on industrial level – mostly based on mixtures.

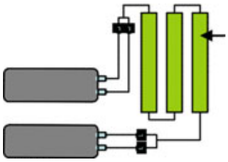
One of INVENTEC goals is to bring our know how to the elaboration of this substitution solutions. A link has to be found between the provider of the chemical solution and the OEM.

INVENTEC strategy is to be this connector.

Another INVENTEC's goal is to minimize the environment impact of SF_6. So since more than 15 years, in a conventional and voluntary framework, the recovery and SF_6 treatment was organized and introduced in a real integrated and efficient circular economy system, which has become today a reference and performed to prevent the emission of 5 millions tons of CO_2 equivalent for SF_6.

It is primarily with the end users and OEM that this has been possible. It was necessary to study the normative issues on the acceptable quality of the recycled product after regeneration and to make accept the second product brought to life by the market.

After regeneration SF_6 conforms to the IEC 60376 standard.



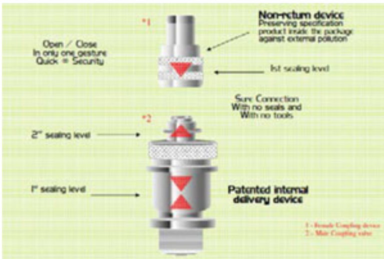
Analyses processed by the laboratory on the products on arrival, and also on the treated product have been put in place to ensure a consistent level of quality.

The aim was to bring together a chain of professionals in electrical distribution and to make them accept the recycle product as well as new SF_6 at a time when such use was not or undeveloped. Steps had to be undertaken with MV and HV circuit breaker manufacturers so that reclaimed specifications are accepted. For dielectric application in MV and HV circuit breaker using SF_6 we get an average of 15 tons per year of SF_6 is 340,000 tons CO_2 equivalent per year or 15-year 5.1 million tons of CO_2 equivalent.

1.2 DIA 5

GREENWAY

After the recovery process, INVENTEC decided to support his clients not only to collect and regenerate the used SF_6 but also to take in account the global SF_6 chain. Based on the INVENTEC eco label called Greenway INVENTEC decide to implement a new leak reduction approach with a unique connection system from the SF_6 packaging to the Client installation.



With this quick connection system for SF_6 called “Clip’n use” with a flat face sealing, emissions during disconnection and connections operations are less than 10^{-3} cm^3/s, and we can estimate that a user working with Clip’n use connector avoids to issue approximately 300 kg of SF_6 per year, or about 7000 tons of CO_2 equivalent per user. Dehon group, decided to go further and to implement a continuous sustainable development approach. While maintaining our solutions at a high level of technical and economical performance, we also define our products by their key impact parameters on health and environment.

If our engineers improve, significantly, 1/3 of parameters without degrading any of the other, we give the Greenway “label” to this product. If we do not improve further the product within the next 5 years, we take the label off.

The objectives of Greenway are clear: more impact in the processes but less impact on health and environment, this is the future of chemicals for high tech industries …

1.3 DIA 6

Greenway approach is in the frame of health and safety protection, and technical performances. Greenway also covers our services; we apply this approach to SF_6 recycling programs with our SF_6 customers.

Despite SF_6 use in a close and airtight chamber, responsible action to reduce emissions is necessary at each steps of use: tests, maintenance, end of life. This is particularly important as there the substitution is just having the first steps and the actual equipment will keep alive for many years.

The 6 impact parameters measured by INVENTEC are:

1. leak rate during filling of equipment
2. leak rate during equipment installation
3. leak rate during maintenance (even after electrical incidents)
4. leak rate during dismantling
5. recovery rate (compared to new product sales)
6. re-use rate.

If we significantly improve 2 of these parameters, we will give to this service the Greenway stamp.

This approach is implemented in EUROPE with our customers.

2 From Craddle to Craddle

2.1 DIA 8

SF_6 is still used in several fields: MV/HV/UHV transformers and breakers, radars, particle accelerators, electronic microscopes…

SF_6 is filled or recovered in many steps of the operations: Tests, failure, dismantling, controls, transfer equipments…

The challenge in that field is the following one: despite of increasing quantity of gas insulated systems, we have to decrease the quantities which will be consumed.

2.2 DIA 9

During all these steps, we need to strongly limit the emissions.

The energy developed by the electrical arc in the equipments is so high that the producer's need to decrease this energy with a very strong dielectric agent. The SF_6 molecule could be modified during the capture of the energy of the electrical arc and coming back on a normal molecule design. The electrical arc energy is a form of plasma. The SF_6 density is very helpful to reduce the electrical damages in the switchgears application.

After several electric arc the SF_6 re composition is not complete and some various decomposition products could be produced. Some of them like SO_2 or S_2F_{10} could be toxic or corrosive. When some levels are reached indicated in the IEC standards, or internal decision at the customer, the used SF_6 need to be taken away and replaced.

At the beginning of the SF_6 story the main way was to replace the use SF_6 by new product and exhaust or destroy the used SF_6.

To reduce the carbon foot print of the SF_6 production but also the foot print of the destruction of used SF_6 destruction INVENTEC decided to implement a recovery and regenerating process.

It was the first circular economy process implemented for the SF_6 application.

2.3 DIA 10

What are the key points where we have to be very sensitive? Substitution/RE USE/IMPROVEMENT OF THE PROCESS.

2.4 DIA 11 Substitution of SF_6

A lot of efforts have been paid in order to find alternative gases. The substitution of this gas is just starting and tests are done on industrial level—mostly based on mixtures. INVENTEC provides its services to its customers in the following fields: packaging, transport legislation, packaging, treatment of waste products, elaboration of mixtures.

2.5 Dia 12 Recycling

The reclaiming center must have the required agreement to process such gas. In the case of our company, INVENTEC has got

- A plant classified Seveso high level (which means the presence of high risks products and of skilled workers trained in the processing of these gases)
- And a state authorization for the activity of trading and processing of waste.

Different ways of analyzing the gas on site are available.

The multi analyzers allow checking on site the content in H_2O/HF/purity/SO_2.

With hygrometers you can check the moisture content (chilled mirror or capacitive sensor). These on site analysis are processed after the purification step made by the gas transfer unit. If the impurities contained in the gas are not acceptable for its re use in the equipment, it has to be send back to the reclaiming center.

The reclaim of used SF_6 has to be done:

- In dedicated packaging with steel valves because brass is not compatible with corrosive gases. This operation has to be done with dedicated equipment, including a high vacuum of the systems in order to minimize the losses at the atmosphere.
- The polluted gas must be transported by dedicated transport companies.
- All these operation are done within the frame of administrative procedures, with specific documents which have to be filled such as:
  - Identification of waste
  - Certificate of acceptance issued by our company
  - Document for the follow up of industrial waste.

2.6 Analysis at Reclaiming Center

Before processing, the used product, it is necessary to know precisely what contaminants are present in the polluted SF_6 and in which quantities for each contaminant.

Therefore the first step is to analyse the polluted gas.

INVENTEC's laboratory is equipped to analyse SF_6 on the liquid phase as stipulated in IEC 60376 recommendations.

The following analyses are performed.

Purity/Water content/Air/Acidity in HF/S_2F_{10}/Non volatile residues (oil) Oil content.

These analyses are performed before the treatment of SF_6 in order to determine whether the product can be retreated or not.

If the product can not be retreated according to the impurities, it is sent to specialized companies which have the authorization to destroy it by incineration.

We must say that more than 90% of the quantities received for treatment are in the frame of these data.

Once the product has been received at INVENTEC reclaiming center and analyzed, we proceed to the purification of the gas.

As far as air is concerned, when its content is too high (more than 10,000 ppm wt): the non condensable gases are separated from SF_6 by distillation.

As far as the other contaminants are concerned, the gas is processed through a large column filled with Soda ash/Activated alumina/Active charcoal/Molecular sieves/Tissue rings/Filters.

A study has been processed by us during 1 year in order to determine the quality of adsorbents that have to be used/quantity of each component/thickness of each layer/speed of transfer of SF_6/pressurization level for transferring SF_6 through the column.

At the exit the product is re analysed in order to make sure that we get a gas that meet the IEC 60376 standard.

As a conclusion we can say that after several years of experience, qualitative, quantitative and financial advantages have been issued.

Qualitative advantage in terms of purity: the recycled SF_6 has really to be considered as a real product which matches the electricity request in terms of purity.

Quantitative advantage—recycling the gas allows re-using it and saves quantities.

Financial advantage the reprocessing of SF_6 allows to

- Avoid destruction cost
- Pay less than new product.

2.7 DIA 13 Better in Process

In terms of equipment, several improvements have been made with the gas recovery units for a better recovery and filtering SF_6 on site. We can now achieve depression until 1 torr which minimizes the quantity of gas rejected at the atmosphere. This equipment allows a filtering of the impurities until 0.1 microns and to dry the gas until 12 ppm wt, but in limited quantities.

INVENTEC issued the Clip'n use valve which allows reducing leaks during connections and disconnections operations.

Many progresses have been done on the gas transfer units—the level of 1 Mbar vacuum can be reached quite easily.

At least INVENTEC takes care of the gas contained in the end of life HTA cells—and reprocess it as well.

This is one of INVENTEC contributions to protect the environment.

5BIOP a Biocomposite for Electrical Application

Wassim Daoud, Laurence Courtheoux, Philippe Depeyre and François Fesquet

Abstract D&D Intelligence, has developed an innovative biopolymer for packaging, electrical equipment, automotive, home and office accessories, etc. Our project aims to perform a new biocomposite using PLA and alfa fibers: PLA: • Polyacide lactic: a biopolymer produced from corn. • Alfa: a wildly plant very abundant in the desert of North Africa (4Mt/year) It associates innovation and sustainability: • Less waste: biodegradable. • Less resources depletion: alfa fibers culture does not necessitate human intervention. • Cost reduction. • Social employment. • Partnership from Europe and North Africa. • A good aspect. • New markets: packaging, home and offices decoration,…. • A patented solution. • LCA performed: less impacts on the environment. Our paper presents 5BIOP specifications and environmental characteristics.

Keywords Biopolymers · Biocomposite · Natural fibers · Electrical insulation

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1 Introduction

On the last ten years, the biopolymers were considerably developed. All industrial sectors work on the subject. The first applications were initially interested in the packaging and building and then widened to the automotive, electrical equipment, sports equipment, etc. These areas are heavily consumer plastic of materials that are not produced locally. Production of biomaterials in the world will be increased fivefold by 2020 (JEC Composite Magazine No. 73) (Fig. 1).

Based on this observation, we performed a project of reducing the environmental impact and costs relating to such materials. The FiveBiop project is to develop a range of biopolymers composed of bio sourced matrix and wild plant fibers. The matrix can be from the polymerization of sunflower oil, rapeseed oil, starch, etc. Fillers commonly used are glass and carbon fibers, silica, and more recently flax fibers and hemp. However, these fibers are industrialized and require significant transformation phase. It is therefore to propose an alternative solution using naturally available fiber and abundant way. Indeed, there are a variety of unexploited plant fibers present in large quantities in the Mediterranean: palm alfa, raffia, kenaf, etc. Currently, the use of these fibers is limited to domestic use, crafts and paper industry. The existing deposits are very important especially for alfa. This is why we focused on this category of fibers. Indeed, it is assumed biomaterials higher cost than synthetic materials and use of food resources. The use of wild fibers reduces the cost of the material while preserving arable land. The purpose of this project is to develop a more environmentally friendly and economical material.

This work was conducted in collaboration with IUT Nîmes (Technology University Institute), SKZ, Eco-presence with the support of Languedoc-Roussillon Region.

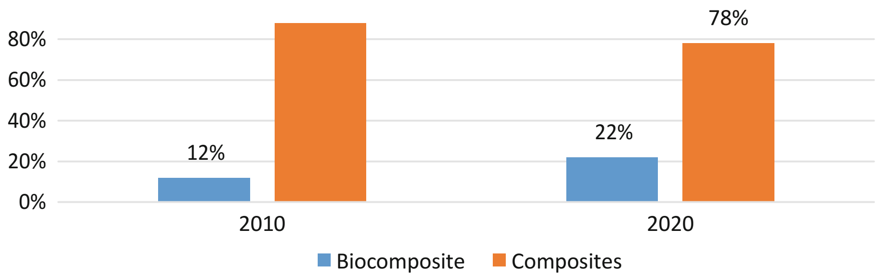

Fig. 1 Evolution of biocomposites in European market 2010–2020

2 Alfa Fiber

The alfa Latin name is Stipa tenacissima. This is an herb and is a member of the grass family. It is a permanent plant that does not disappear in the winter and grows independently, forming webs. Due to the low water consumption alfa is endemic in the western Mediterranean region, a rather dry region. The territorial distribution is shown in the Table 1 (Fig. 2).

Alfa has an ecological, economic and social advantages. It does not need insecticides or pesticides harmful to the environment and consumes water from the atmosphere. Usually, the fiber structure is heterogeneous. Smaller parts in the fibers are filaments or fibrils having lengths of 2–5 mm and diameters from 5 to 10 mm.

Alfa is received in sheets as they occur in nature. The first step is to dry in the sun. After that, the sheets are sent to a carding operation. This operation aims to obtain alfa fiber and remove foreign materials (Table 2).

Table 1 Territorial distribution of alfa

Country	Algeria	Morocco	Tunisia	Libya	Spain
Area(ha)	4,000,000	3,186,000	500,000	350,000	30,000

Alfa herbs Alfa fibers with PLA

Fig. 2 Photos of alfa plant and fibers

Table 2 Alfa fiber property

Property	Density	Elongation (%)	Breaking stress (MPa)	Young Modulus (GPA)
Value	1.4	1.5–2.4	134–220	13–17.8

3 Polylactic Acid Pla

The polylactic acid is biopolymer. PLA was discovered in 1932 by Carothers. The production of PLA has numerous advantages including: (a) production of the lactide monomer from lactic acid, which is produced by fermentation of a renewable agricultural source corn; (b) fixation of significant quantities of carbon dioxide via corn (maize) production by the corn plant; (c) significant energy savings; (d) the ability to recycle back to lactic acid by hydrolysis or alcoholysis;

(e) the capability of producing hybrid paper-plastic packaging that is compostable; (f) reduction of landfill volumes; (g) improvement of the agricultural economy; and (h) the all-important ability to tailor physical properties through material modifications [1]. Briefly, PLA is based on agricultural (crop growing), biological (fermentation), and chemical (polymerization) sciences and technologies. It is classified as generally recognized as safe (GRAS) by the United State Food and Drug Administration (FDA) [2].

3.1 5BIOP Properties

Extrusion is the first step in the implementation of the biopolymer. During extrusion, the polymer pellets are melted and the fibers are introduced as filler. The compoud is an aggregate of PLA and Alfa fiber. The extrusion step optimizes the dispersion of alfa fibers in the PLA. After that, the material is mixed within a compounder.

3.2 Electrical Properties

We only have principal electrical properties of 5BIOP: dielectric dissipation, permittivity, resistivity and breakdown (Table 3).

According to several reports on temperature dependence of electrical properties of PLA, PLA has been indicated to cause changes in electrical properties near the glass transition temperature. Figure 4 shows the temperature dependence of Dielectric dissipation factor, permittivity and resistivity. As the temperature

Table 3 5BIOP dieletric properties

Property	Dielectric dissipation factor (ρ) at 1 MHz	Permittivity	Resistivity Ω cm	Dielectric breakdown kV
5BIOP	0.01	3.1	4.3×10^{17}	35–40
PVC	0.01	5	10^{16}	40

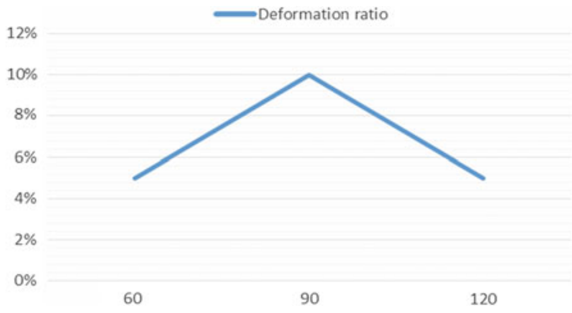

Fig. 3 Thermal dependence on deformation of PLA

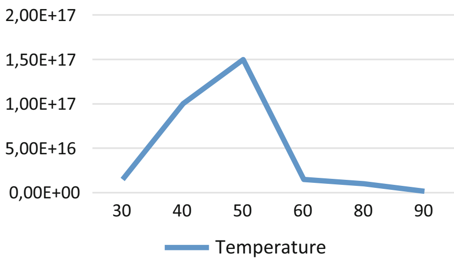

Fig. 4 Resistivity Temperature dependence

increases, ρ decreases significantly in the vicinity of Tg (60 °C), but does not decrease at higher Tg. In fact, these properties are comparable to PVC ones. So, it is possible to assume that 5BIOP could be used as a dielectric material (Fig. 3).

3.3 Mechanical Properties

The mechanical tests were carried out on a dynamic part of a low voltage electrical switch for indoor use. They include tensile strength, flexion, mechanical shock, flame spread, chemical compatibility, biodegradability. These test confirm that the 5BIOP could be used in some electrical applications (Fig. 5).

The Figs. 7, 8, 9, 10 and 11 show the results of mechanical tests: flexion, tensile, flame spread, biodegradability and chemical compatibility (Fig. 6).

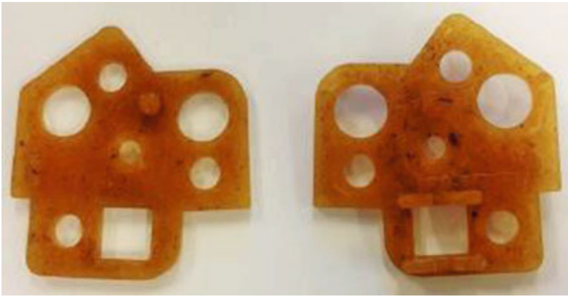

Fig. 5 Dynamic part of an electrical switch

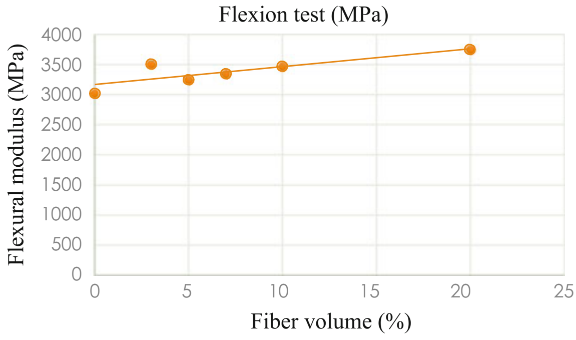

Fig. 6 Flexion test

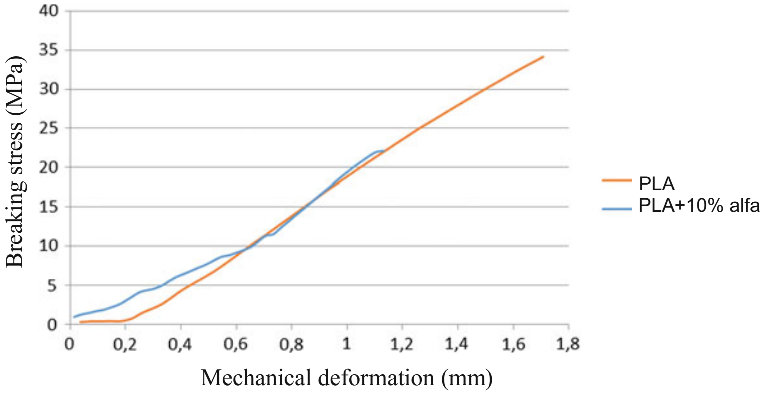

Fig. 7 Tensile test of PLA and PLA + 10% Alfa

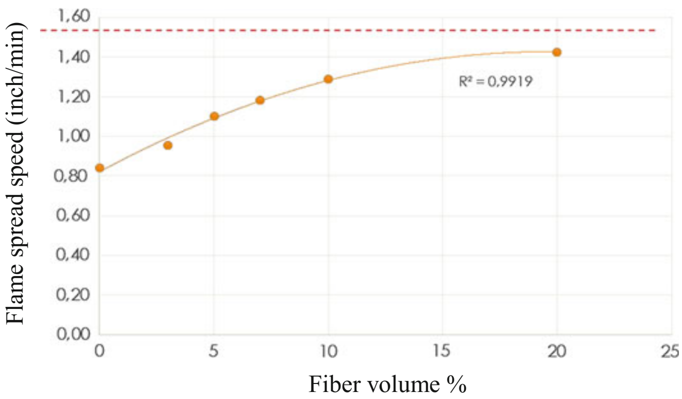

Fig. 8 Flame spread of PLA + Alfa

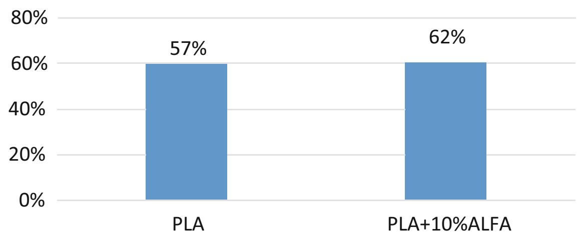

Fig. 9 Biodegradability test

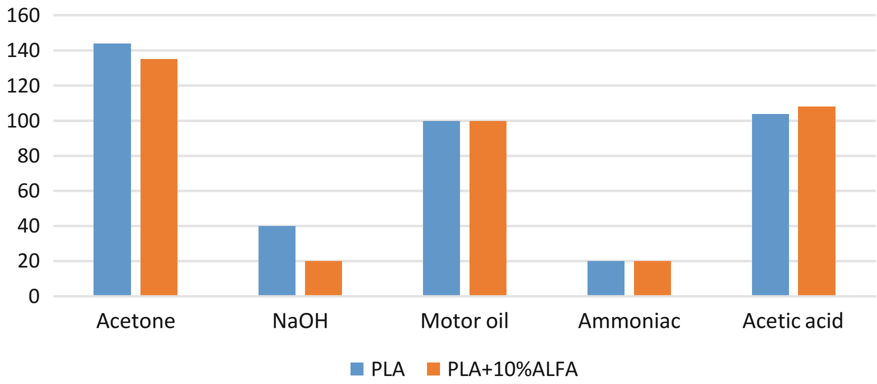

Fig. 10 Volume evolution after 100 h immersion

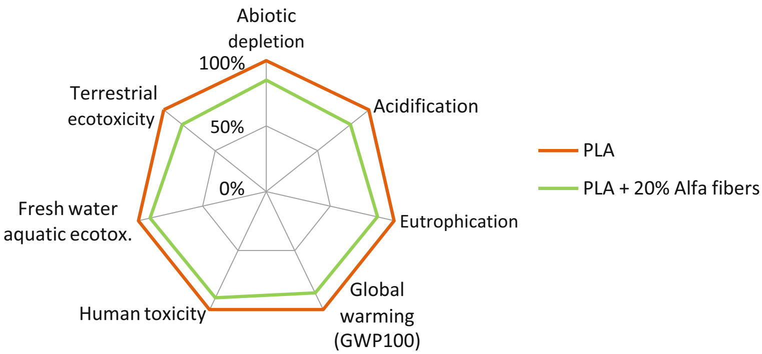

Fig. 11 Life cycle assessment of PLA and PLA + fibers

The biodegradability test was performed conforming to ISO20200 standard. It consists on the test of the material degradation in anaerobic environment during 50 days at 60 °C. It shows that the 5BIOP was biodegraded at more than 60% (Table 4).

The parts comply with the EN 60529 standard and have a body fluids protection degree of IP X7.

Table 4 Comparaison of main mechanical properties of PVC and PLA + alfa

	PVC	PLA + 20% Alfa fibers
Density	1.4	1.24
Tensile strength (MPA)	52	59
Elongation at break (%)	50–80%	40%
Flexural modulus (MPA)	2700–3000	3700

Table 5 Greenhouse gas emissions in kg CO2 eq./kg of polymer

Polymer			PLA	PP	PET	PC
GWP eq/kg	kg	CO2		1.9	3.2	7.6

4 Environmental Properties

Biopolymers can reduce significantly the greenhouse gas emissions (Table 5).

The use of alfa fibers contributes to reduce the environmental impacts of PLA polymer. The Fig. 11 shows better environmental performances of PLA with 20% of alfa fibers [3]. The addition of alfa fibers allow to reduce up to 20% of environmental impacts of PLA.

5 Conclusion

5BIOP composite is an innovative bipolymer. It uses natural alfa fibers without any human intervention or additional treatment. The performed tests show that this material can be used for indoor low voltage application. However, we do recognize that these tests are not sufficient and should be improved with additional ones. In another side, the 5BIOP present good greenhouse performances. But, we do realize that it could have less good impacts in other environmental parameters as eutrophication or air acidification.

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State of the Art Process of End-of-Life Treatment for SF_6 Medium Voltage Equipment

Giovanni Zaccaro, Jean-Marc Biasse, Renzo Coccioni and Philippe Leoni

Abstract In a world where recycling is a word commonly used in our everyday life, it is important to explain that not all processes dealing with obsolete Medium Voltage equipment (end-of-life management, scrapping or destruction) have the same impact on the environment. This paper highlights the key points that differentiate a state of the art process of end-of-life treatment for SF_6 Medium Voltage equipment from a basic dismantling process. It shows that it is necessary to analyze every phase performed in order to limit SF_6 emissions to the lowest possible value.

Keywords Sulphur hexafluoride · Global warming · Environmental impact · Recovery

1 Introduction

Sulphur Hexafluoride (SF_6) gas is a well known insulating and breaking medium used for decades for transmission and distribution equipment. It is also a very powerful greenhouse gas with a GWP (Global Warming Potential) of 23,500 [1]. In Europe, legislation requires owners of equipment to recover residual gases prior to its disposal, as stated in Regulation (EU) No 517/2014 [2]. It is, however, mainly

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for the environmental impact that special care must be taken during the disposal of Medium and High Voltage Equipment. Owners of equipment should be aware that not all end-of-life treatment processes are the same from an environmental point of view. Although regulations and standards set rules and guidelines for this type of service, modern technology, experience and knowledge enable us today to go beyond regulations, namely a step further towards a greener, low carbon world.

The aim of this paper is to inform on the latest know-how and technological progress for the disposal of MV equipment.

It will be necessary to analyze every step of the process in order to reach an optimized and *state of the art* disposal process for SF_6 Medium Voltage equipment. From the moment the equipment is decommissioned up to its disposal, it will go through the following 5 main steps:

- Transportation
- SF_6 Recovery
- Dismantling
- SF_6 Reclaiming or destruction
- Storage of cylinders containing used SF_6.

2 Transportation

Before transporting the equipment from the location where it was installed to the workshop where it will be dismantled, special care must be taken on how the equipment is strapped to the pallet to avoid dangerous movements during transportation. It is necessary to avoid equipment from tilting and dropping, because this can create cracks in the SF_6 enclosure and therefore leaks (Fig. 1).

It is advisable to gather as many units as possible in order to optimize transportation and avoid unnecessary carbon emissions.

But why shall the equipment be transported away? Can't it be treated on site? This is because for MV equipment it is recommended to perform the dismantling process in a closed but ventilated workshop, particularly for safety reasons.

During the recovery of gas, we will reach low pressures of the SF_6 inside the gas chamber. This can lead to implosion (particularly with stainless steel compartments), with the risk of flying objects hitting workmen present in the workshop. Also, performing this operation outdoors may disturb operators' concentration level due to wind, rain and other meteorological conditions.

It is universally accepted that SF_6 presents no danger to life apart from the fact that, since it is denser than oxygen, a prolonged exposure to an environment rich in SF_6 could lead to asphyxiation. This danger is avoided by adequate ventilation. An O_2 detector shall be available for the operator to inform about risks due to accumulation of SF_6.

Fig. 1 Correct strapping of equipment to wooden pallets

3 SF_6 Recovery

International Standard IEC 62271-4 [3] states that residual pressure during recovery should be below 2 kPa (20 mbar). Modern SF_6 pumps can operate well beneath this value, without the operator having to wait too much time. Let us compare the amount of SF_6 which we will avoid releasing to the atmosphere if 0.1 kPa (1 mbar) had been reached instead, and most of all, its CO_2 equivalent.

Let's assume your equipment has an SF_6 filling pressure of 130 kPa (1300 mbar) absolute and the filled SF_6 mass is 2.5 kg.

If recovery is processed up to 2 kPa (20 mbar) vacuum level, only 98.46% of SF_6 will be recovered from the equipment, which means 38.5 g lost per unit. For 100 units, the equivalent CO_2 emission will be 90 tonnes!

With 0.1 kPa (1 mbar) vacuum level, CO_2 equivalent emission will be reduced to 4.5 tonnes, with 99.92% SF_6 recovery rate.

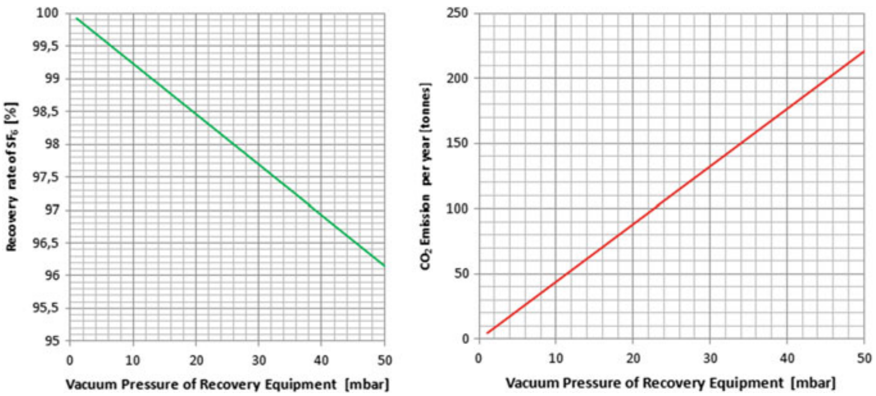

Fig. 2 On the *left*, Recovery rate of SF_6 versus Vacuum pressure of recovery equipment. On the *right*, CO_2 emissions per year versus Vacuum pressure of recovery equipment. Both graphs have been drawn by assuming 130 kPa (1300 mbar) initial pressure, 2 kPa (20 mbar) final pressure, 2.5 kg of SF_6 initially inside the equipment and 100 units of equipment

The graph on the left of Fig. 2 shows how the recovery rate of SF_6 increases with decreasing vacuum pressure of the recovery equipment. It is therefore best to reach a low vacuum pressure inside the obsolete equipment. On the right, the CO_2 emissions increase as the vacuum pressure of the recovery machine increases. Once again, it is recommended to reach the lowest possible vacuum pressure when recovering SF_6.

As stated in the paragraph on transportation, certain equipment may not withstand low pressure during recovery and may implode. Membranes, gaskets, welded joints and even sheet metal compartments may not bear the pressure. As a consequence, the recovery operation may not be completed and residual SF_6 gas may escape to the atmosphere. To avoid this from happening, specific cabinets exist. The principle is to lower the pressure inside and outside the equipment at the same time. Therefore it will be possible to reach low absolute pressures inside the equipment, in order to evacuate all residual SF_6 gas, and at the same time avoid stress on mechanical sealing parts. Potential flying parts which could cause injuries will also be avoided (Fig. 3).

Each equipment needs specific tools to connect the pump to the SF_6 container. The manufacturer has the best knowledge and experience of its products and will be able to provide the right connections that will avoid leaks. Furthermore, it is necessary to verify that the recovery equipment (i.e. the pump) is free of leaks. An SF_6 leak detection unit, also called “sniffing probe”, can be used to perform a leakage check during SF_6 recovery. The tool shall be set at a threshold of 10^{-6} mbar.l/s.

In the European Union, SF_6 recovery can only be performed by operators having followed the specific training and holding a certificate released by an approved

Fig. 3 A cabinet used for gas filling and recovery for MV equipment

certification body of a Member State. This measure, which came in force in July 2008 with the additional Regulation (EC) No. 305/2008, has been extended to other activities in the most recent implementing Regulation (EU) No. 2015/2066 [4]. From the 1st July 2017, operators performing filling operations, installation of manometers, transfer of SF_6 between compartments and all other SF_6 handling operations, including of course recovery, shall also be certified.

4 Dismantling

Inside used SF_6 equipment, there is a high probability of finding gaseous and solid SF_6 decomposition by-products, which are dangerous for operators in case of contact, due to their toxicity and corrosiveness.

For this reason the equipment shall be handled and opened with care after recovery of SF_6 from the equipment. Any risk for the health of the operators shall be avoided. The molecular sieve, an object whose main aim is to absorb humidity contained in the equipment and SF_6, will have absorbed a big part of the by-products. It shall therefore be sorted and put in a specific bin for toxic substances. The inside of the SF_6 tank must be cleaned with an industrial dry vacuum cleaner (H dust class). The tank shall also be neutralized with a caustic soda solution.

5 SF_6 Reclaiming or Destruction

Once the SF_6 is recovered from obsolete equipment and is pumped in correctly labelled cylinders, there are 2 options to choose from for its future: reclaiming or destruction.

Reclaiming gives a new life to SF_6. Experience shows that in 99% of the cases, the used SF_6 which has undergone the specific treatment process (a series of filtrations) can be fully reused. In fact, the treatment process allows it to reach IEC 60480 [5] or even IEC 60376 [6] requirements.

Another choice is to proceed to SF_6 destruction. There exist several processes to destroy SF_6; from discharge activation, like in the non-thermal plasma process [7], to the decomposition at hot surfaces, to thermally activated SF_6 reactions with metals and metal oxides [8]. These processes transform SF_6 in environmentally compatible fluorides, sulphides and sulphates.

However, the most common is the destruction in high temperature dump combustors (temperatures >1000 °C). Although this solution is economically favourable compared to reclaiming, it has several ecological drawbacks:

- The recycling loop is broken. There will be no reuse of the decomposed SF_6 molecule. New, valuable resources will be pulled out of the earth, processed in factories, shipped around the world, and then wasted in incinerators.
- Emissions: even the most technologically advanced incinerators release thousands of pollutants that pose considerable risk to the health and environment of neighbouring communities [9].
- Climate change: all incinerators emit carbon dioxide (CO_2). According to the U.S. EPA, "waste to energy" incinerators contribute far higher levels of greenhouse gas emissions and overall energy throughout their lifecycles than source reduction, reuse and recycling of the same materials [10].
- Energy: in order to reach high temperatures (combustion at 1000 °C and post-combustion at 1200 °C), a considerable amount of energy will be needed.

The recommendation purely from an environmental point of view is to reclaim the SF_6 and close the SF_6 life cycle loop.

6 Storage of Cylinders Containing Used SF_6

Cylinders containing used SF_6 should not be kept longer than 2 years before they are checked and newly certified, in order to avoid any leakage. They must have an orange or yellow strap around the bottleneck and should be properly labelled (check with an SF_6 gas recycler for the proper label codification). Once the cylinder is emptied in order to recycle the SF_6 gas, it should be cleaned inside and outside and newly certified before using it again.

Cylinders leakage test should be performed frequently (frequency to be adapted locally to the period of storage) to ensure leakage rates below 1×10^{-6} mbars.l/s

Fig. 4 Example of a “Zero Emission” coupling valve, which avoids the SF_6 loss of the dead volume

during the whole period of storage (including during filling up of the drums at the workshop).

SF_6 cylinders are generally equipped with valves (DIN 477—Part 1: Type A, 1” No. 8 [11]) and screw-in fittings, which are different from those used in containers for new gas to prevent inadvertent filling and contamination of new SF_6. The valves are made of stainless steel to withstand corrosive decomposition products [12].

New generation “Zero Emission” coupling valves have been recently designed to dramatically reduce SF_6 loss during connections and disconnections. Thanks to this new concept, the so-called “dead volume” loss is avoided (Fig. 4).

7 Conclusions

Modern tools, technologies and know-how are today available. This *state of the art* end-of-life treatment for SF_6 Medium Voltage equipment will increase the safety of personnel while considerably limiting the environmental impact. All of the process steps will contribute to it:

- Transportation: caution during handling and strapping of the equipment to avoid tilting, dropping and damaging of equipment, and hence potential leaks.
- SF_6 recovery: it is now economically possible to go beyond regulations and standards to limit emissions. A recovery cabinet which reaches a vacuum pressure of 0.1 kPa is the utmost technological standpoint. It is recommended to perform the end-of-life treatment through the equipment manufacturer. The operators handling the gas must hold a certification in Europe.
- Dismantling: the molecular sieve contains the most toxic substances. It must be disposed of according to toxic wastes regulations.
- SF_6 reclaiming or destruction: reclaiming enables up to 99% of the gas to be reused in future applications. During destruction, although this is generally economically more interesting, the ecological impact is higher since the recycling loop is broken, leading to emissions of CO_2 and pollutants.
- Storage of cylinders containing used SF_6: regularly check the cylinders for leaks. Avoid dead volume leaks thanks to “Zero Emission” coupling connections.

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Validation of a New Eco-friendly Insulating Gas for Medium and High Voltage Equipment

R. Maladen, C. Preve and D. Piccoz

Abstract This paper deals with the validation steps of alternative gases to SF_6 for high and medium voltage switchgear applications. It is focused on technical properties of the potential candidates. SF_6 is widely used for several decades in high and medium voltage switchgear as insulating medium. Indeed, thanks to its excellent physical properties, low toxicity and high stability, SF_6 brought numerous advantages like compactness, effectiveness, reliability, However, despite these very interesting properties, this gas has a very high global warming potential (GWP = 22,800), and for this reason, alternative candidates must be found to replace it. This paper proposes a procedure to evaluate and validate potential candidates to replace it and gives an overview of the main properties of the most interesting candidates.

Keywords SF_6 alternative · Insulating gas · Electrical equipment · Switchgear · GWP · Validation · Dielectric · Environmentally friendly · Toxicity

1 Introduction

SF6 gas is widely used pure in high and medium voltage applications thanks to its exceptional physical properties including dielectric strength, stability, low toxicity and so on, … However, because of its huge environmental impact, the use of SF_6

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gas will gradually decrease in the coming years. Indeed, the environment protection is a point of attention for politicians, customers and high and medium voltage equipment suppliers. Main manufacturers are strongly involved in this topic and have published many papers [1–14]. However until today, the compromise between performances, environment protection, size, toxicity and cost has not yet been found and it clearly appears that it would be difficult to provide to users competitive products without considering the validation of a new gas. This paper describes a method to validate alternative gas to SF_6.

2 Alternative Gas Pre-selection

Ideally the gas must be non toxic, non corrosive, non flammable nor explosive and have a low GWP (Global Warming Potential) and a low ODP (Ozone Depletion Potential). Additionally it must have a low boiling point to allow using it in sufficient quantities at the minimal temperature of use.

Considering the expected properties listed above and in spite of the wide number of chemicals available on the market, only a limited number of candidates have properties suitable for their use in MV equipment (Table 1).

As a reminder, LC50 (50% lethal concentration) means that the concentration of the chemical in air causes the death of 50% (one half) of a group of test animals within a specified time.

Table 1 Characteristics of the gases

	CAS number	Boiling point (°C)	GWP	ODP	Flammability	Toxicity LC50 4 h/rat (ppmV)
SF_6	2551-62-4	−64*	22,800	0	No	
Fluoroketone $C_5F_{10}O$	756-12-7	26.5	1	0	No	>20,000
Trifluoroiodomethane CF_3I	2314-97-8	−22.5	0.4	Very low	Low	160,000
Hydrofluoroolefin HFO1234zeE	1645-83-6	−19	6	0	Low	>207,000
Hydrofluoroolefin HFO1234yf	754-12-1	−29	4	0	Medium	>405,000
Hydrochlorofluoroolefin HCFO1233zd	102687-65-0	18.3	7	Very low	No	120,000
Fluoronitrile C_4F_7N	42532-60-5	−4.7	2100	0	No	<15,000

*Sublimation point

3 Characteristics of G S

3.1 Physical Parameters of Gas and Gas Mixtures

As SF6 has a very low boiling point (−64 °C), it can be used alone, except for HV equipment with high pressure and very low operating temperature.

For medium voltage equipment the most common minimal temperature of use is −15 °C. At this temperature, only CF_3I, HFO1234zeE and HFO1234yf could be used alone. The other candidates should be mixed with a buffer gas (CO_2, N_2, O_2…) in order to have a total pressure in the equipment always higher than atmospheric pressure to easily detect potential leakage and avoid entry of polluted air.

The saturated vapor pressure as a function of temperature and the boiling point of each gas of the gaseous mixture (in the case of mix) is an important parameter to know. The Fig. 1 shows the evolution of the saturated temperature. The evolution vapor pressure of $C_5F_{10}O$ and HFO1234zeE as a function of the total pressure of gas shall be defined on the range of temperatures (from the temperature of storage up to the maximum temperature of gases in normal conditions). The condensation temperature may also be relevant to know.

Once the mix is defined at ambient temperature, it is necessary to calculate the global warming potential of the gas mixture taking into account the buffer gas. The real impact on environment is given by the quantity of equivalent CO_2 and depends on the mass of gas inside the electrical equipment and its GWP (Table 2).

Fluoroketone $C_5F_{10}0$, CF_3I and HFO have a negligible CO_2 equivalent impact while fluoronitrile has an impact not so far from SF_6 mixture with air. Indeed, dielectric SF_6 properties are not linear with % of air mixture, and then only 20% of SF_6 enables to reach 80% of dielectric property of pure SF_6. This dielectric property enables to reach dielectric performance on SF_6 switchgear with slight modifications.

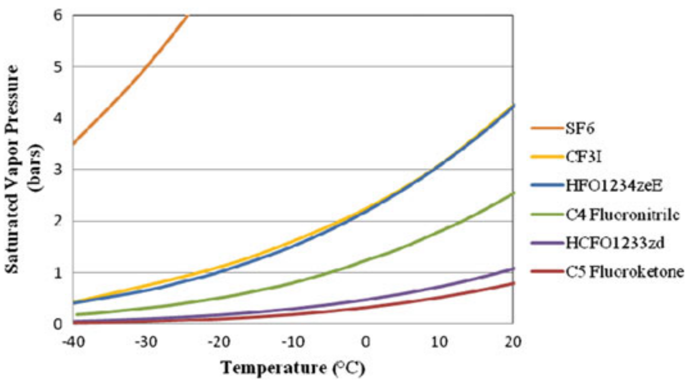

Fig. 1 Evolution of saturated vapor pressure some potential alternatives to SF_6 as a function of temperature

Table 2 Impact on the environment of the potential candidates to the replacement of pure SF6- for MV applications

Potential candidates	SF_6 (20%) + air (80%)	$C_5F_{10}O$ + air	CF_3I	HFO1234zeE	HFO1234yf	CFO1233zd + air	C_4F_7N + air
Dielectric characteristics(BIL) in direct line	$0.8 \times SF_6$	$0.85 \times SF_6$	$1.2 \times$ SF6	$1 \times SF_6$	$1 \times SF_6$	$0,9 \times SF_6$	$1.2 \times SF_6$
GWP (Global Warming Potential)	12,910	0.6	0.4	6	4	4	1890
Eq tons CO2 (GIS: 250 L –1.3 bar abs)	8.9	0.0005	0.0003	0.009	0.006	0.002	3.1

Then the candidate can be a gas used alone, used with a buffer gas or a mix of different gases (for instance $C_5F_{10}O$ + HFO1234zeE + dry air). In the latter case, it is necessary to check if there is a reaction between these gases or not. This kind of verification is especially of great significance when several fluorinated gases are mixed together and then, when partial pressure at low temperature does not follow the perfect gas law but another one such as the Raoult's law [14] for instance. In this case and depending on the selected molecules it is difficult to predict the partial pressure of each component at low temperature as well as the insulating performance of such mixture at the lowest temperatures. The Fig. 2 shows the evolution of the saturated vapor pressure of a mix of 3 gases ($C_5F_{10}O$, HFO1234zeE, N_2) as a function of temperature.

In case of gas mixture, especially when the densities of the gases are different, the homogeneity of the gases shall be checked. A proper way to check it consists to fill a vertical pipe (for instance 2 m) at a given temperature from its bottom, in starting by the less dense gases and continuing by the denser. The concentration of the different gases is measured from both sides of the pipe. It can be considered that the mixture is homogeneous when the different concentrations of gases measured from the top and the bottom are identical.

The means to check the pressure of gas inside the tank (measured by pressure sensor or densimeter) shall allow to detect any leakage for the whole temperature range. The tank of switchgear and the safety features shall be designed taking into account the pressure inside the tank on the whole range of temperatures, particularly at the storage temperature, at the minimal operating temperature and at the maximal temperature of gas.

The real concentration of the different components of the gas mixture is difficult to calculate at the minimal operating temperature (Raoult's law applies with possible liquefaction, adsorption of gases by molecular sieved and other materials like silica,…) while these concentrations are necessary to determine the dielectric and breaking capacities.

Dielectric tests at low temperatures are important because some candidates showed a decrease of dielectric insulation properties at the lowest temperatures.

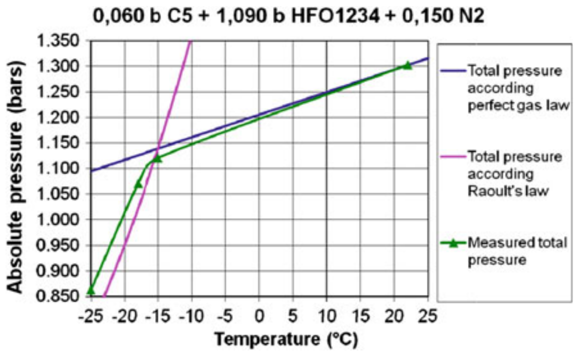

Fig. 2 Evolution of the total pressure of a gaseous mixture (0.06 bar C5 K + 1.09 bar HFO1234zeE + 0.15 bar N_2) as a function of temperature

3.2 *Dielectric Properties*

Dielectric tests are performed on mock-up in order to understand the physical phenomena but also on switchgear, according to IEC standards, to validate the dielectric withstand of medium voltage equipment.

Dielectric tests (lightning impulse withstand voltage and short-duration power–frequency withstand voltage) were performed at the minimal functional density of gas, i.e. at the minimal temperature of use (−15 °C or −25 °C). Partial discharges tests were performed at the minimal functional density of gas too.

<u>Tests on mock-up:</u>

Dielectric strength measured by gas suppliers in a homogeneous configuration is an important but not sufficient parameter to evaluate the insulating properties of a candidate. Indeed, high and medium voltage switchgear is complex apparatus that generally cover a wide range of electrical fields distribution and electrical field on surface of insulators.

In order to investigate this point, specific mock-ups were built to cover both homogenous and heterogeneous fields.

The mock-up for homogeneous field is made of two electrodes of diameter 12 mm separated by 12 mm. This configuration leads to a ratio “Maximal electrical field divided by minimal electrical field” of 3, value that is generally considered as representative of homogenous fields that can be met in medium voltage switchgear.

For heterogeneous field, the test configuration has been defined in order to have a ratio “Maximal electrical field divided by minimal electrical field” equal to 11. Here also this value was considered as representative of heterogeneous field that can be met in switchgear. It was obtained with two rods of diameter 5 mm separated by 25 mm (Fig. 3).

For instance, the lightning impulse withstand voltage of $C_5F_{10}O$ + dry air mixture is better in heterogeneous than in homogenous field when it is the opposite for HFO1234zeE.

At the same pressure, pure gases have a similar or even higher dielectric withstand than SF_6. However, the gas mixtures may have, at −15 °C and according to

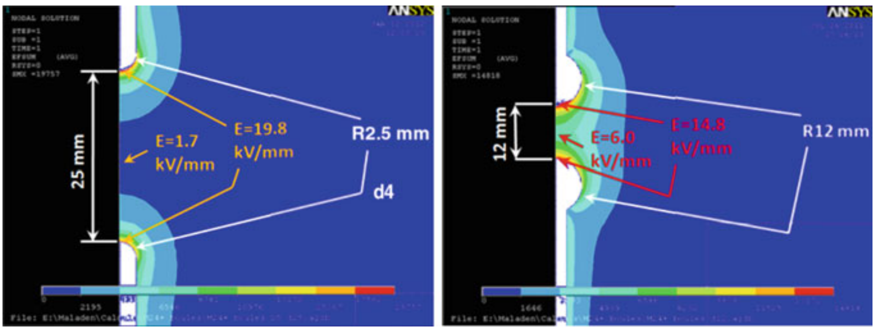

Fig. 3 Simulation of the electrodes with the electrical field

the configuration of electrical field and the kind of test (lightning impulse or 50 Hz), a dielectric withstand lower than SF_6.

For instance, the mixture with C_4F_7N and dry air is, at −15 °C, better than SF6 in BIL test but it is the contrary at 50 Hz.

The mix HFO1234zeE + C5 K + air enables to reach a dielectric withstand close to SF_6 whatever the electrical field.

The insulating performance of a switchboard is not only driven by the insulating distance in gas between two phases or between a phase and the earth but is also sensitive along insulating material. This phenomenon is known as "flashover on surface" (Fig. 4) and can, in some cases, be the weak point of the dielectric withstand of switchgear.

Experiments done during the last years showed that the interaction between SF6 molecules and insulating polymers lead to a better behaviour than what was observed with other candidates.

As this interaction is difficult to estimate, it represents an important input to take into account during the selection of alternative gas to SF_6.

The use of barriers (Fig. 5) is a common solution to increase the dielectric withstand of a product without increasing its size. However, with some candidates, it was observed that there were absolutely no benefits showing that the selection to use this solution. This observation is an additional example of alternative gas to SF_6 is not so obvious because numerous parameters shall be taken into account to design compact switchgear.

Tests on apparatus:

Preliminary power frequency and lightning impulse tests are performed on switchgear with SF6 as reference. In a second step, similar tests are made at the

Fig. 4 Traces of flashover on the surface of a thermoplastic part

Fig. 5 Tests with barriers

minimum temperature of use or at room temperature at the minimum functional density corresponding to the minimal temperature of use. Their performances are compared with those of SF_6 and the best ones are selected for the next steps of validation: tests in the whole range of electrical fields distribution in order to build design rules models, flashovers on surface of insulating materials tests, partial discharges tests, dielectric tests at low temperature, tests with barriers…

Tests on apparatus:

Preliminary power frequency and lightning impulse tests are performed on switchgear with SF6 as reference.

In a second step, similar tests are made at the minimum temperature of use or at room temperature at the minimum functional density corresponding to the minimal temperature of use.

Their performances are compared with those of SF_6 and the best ones are selected for the next steps of validation: tests in the whole range of electrical fields distribution in order to build design rules models, flashovers on surface of insulating materials tests, partial discharges tests, dielectric tests at low temperature, tests with barriers…

Long term behaviour shall also be investigated: the candidates are put under several levels of partial discharges during several months before dielectric tests and gas analysis are carried out to check their stability.

3.3 Making and Breaking Capacity

Making and breaking tests shall be performed according to IEC standards, in identical conditions to the most severe operating conditions of the switchgear, i.e. with the functional density of gases corresponding to the minimum operating temperature.

3.4 Temperature Rise

Temperature rise tests according to IEC standards were performed on several switchboards filled with gases. Results were worse than SF_6 ones but may not require a complex redesign of the apparatus.

3.5 Corrosion and Oxidation

Except for CF_3I, temperature rise tests carried out on electrical equipment and ageing tests conducted on materials did not show oxidation, corrosion and acid attack by the gases.

3.6 Permeability, Tightness and Adsorption

The results of diffusion tests performed at different temperatures on the different polymeric and elastomeric materials to determine the diffusion coefficient of the pure gas in the materials has to be taken into account to evaluate the leakage rate of the electrical equipment.

Adsorption tests were performed to assess the real concentration of the different gases of the gas mixture inside the electrical equipment, especially in presence of CO_2 and desiccant in order to assess the concentrations during the expecting life of switchgear.

3.7 Interaction Between Gases and Materials

The pure gas may react with the materials present in the electrical equipment. It may be degraded itself and/or it may degrade the performance of the materials. The gas mixture and materials were exposed at 2.5 bar and 115 °C (or 80 °C for elastomer) during several weeks. Analyses of gas were done in order to determine whether or not the gas mixture compatible. Tests (i.e.: tensile tests, mechanical impact, deformation and the materials are under load, dielectric withstand in tracking, …) were performed in parallel to check the potential degradation of the characteristics of materials.

3.8 Internal Arc Fault

It is interesting to perform several internal arc fault tests with different values of current and duration because the by-products and their concentration, and as consequence the toxicity, depend on the energy inside the switchboard.

For instance, 16 kA—(0.1 and 1 s) internal arc fault tests were performed on a 24 kV GIS filled with different gases. The gases after internal arc fault tests were analyzed taking into account the humidity of air surrounding the electrical equipment and used for toxicity studies.

4 Discussion and Conclusion

This paper presents the candidates to replace SF6 as dielectric medium or dielectric and quenching medium. In order to guarantee safety for operators during the total life cycle of the apparatus (from manufacturing to the dismantling), in normal conditions like in abnormal conditions (gas leakage, partial discharges and internal arc fault), reliability and expecting life comparable to SF_6 equipment, a program of validation must be defined for the gas alone and for apparatus filled with this gas. This validation does not concern only electrical performances but many other topics such as corrosivity…toxicity, tightness, compatibility between materials and gas. The ideal candidate is not yet found. Some mixtures of gases are not stable, others generate very toxic by-products, are flammable or react very strongly with materials. The new gas should be a compromise between all these parameters which shall be balanced with the GWP reduction.

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