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A multidisciplinary approach to the introduction of the solar photovoltaic technologies in the energy mix

Sophie Avril

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SUJET :

A multidisciplinary approach to the introduction of the solar photovoltaic technologies in the energy mix

Une approche multidisciplinaire à l'introduction des technologies solaires photovoltaïques dans le mix énergétique

soutenue le 21 novembre 2014

devant un jury composé de :

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Summary

The energetic issue is on the top of the political agenda in many countries, for environmental reasons, for its driving role in all the economic sectors, as well as for the energetic independency concerns. This problematic is stressed by the increasing weight of renewable intermittent power sources in the global energy mix. In particular, due to its high potential and the strong national policy support it benefited, solar photovoltaic energy is now a key player in the world energy mutation, and the way it is integrated into the global mix should be carefully performed.

To deeply understand the way solar energy can penetrate and transform the forthcoming energy framework, we adopted a three-level strategy with an multidisciplinary approach to provide some answers to the following questions: i/ how can we situate the photovoltaic power role in future energy mixes?; ii/ due to its main drawback, intermittency, could we provide an optimal design of a system combining storage devices?; iii/ what is the efficiency of the incentive policies that are or have been implemented to accelerate its deployment?

That is why, in a first chapter, the peculiar position of the solar photovoltaic energy in the energy mix is analyzed. After recalling the general issue of future global energetic mixes, we propose a brief description of the different photovoltaic technologies and their promising evolutions in terms of technical improvements and cost reductions. Then, we describe the fast growing photovoltaic market and its consequences both on the electricity mix and the industry sector.

In the second chapter we investigate the issue of integrating such an intermittent energy in the electricity mix, by developing a multicriteria evaluation methodology and a multicriteria under constraint optimization tool which simulates a system composed of photovoltaic panels and storage devices. Applications on a real case in the *Cirque de Mafate (L'île de la Réunion, France)* are presented to illustrate the interest of our method.

Finally, in chapter three, we question the efficiency of different public support policies to the photovoltaic technologies in the most relevant countries. We focus on correlating the installed power capacity with the spent public money and the electricity prices.

Résumé

Les problématiques énergétiques sont au sommet des préoccupations politiques dans de nombreux pays, du fait des enjeux environnementaux inhérents, du rôle moteur de l'énergie dans tous les secteurs économiques ainsi que des préoccupations relatives à l'indépendance énergétique. Cet intérêt est accru du fait de la part croissante des sources d'énergie renouvelables et intermittentes dans le mix énergétique mondial. En particulier, de par son fort potentiel et la volonté politique de soutien dont elle a bénéficié, l'énergie photovoltaïque est désormais un acteur clé dans la mutation énergétique mondiale, et son intégration dans le mix mondial doit être réalisée avec attention.

Afin d'avoir une compréhension approfondie de la façon dont l'énergie solaire peut pénétrer et transformer le panorama énergétique, nous avons adopté une stratégie en trois niveaux avec une approche multidisciplinaire visant à apporter quelques réponses aux questions suivantes : i/ quel sera la position de l'énergie solaire dans le futur mix énergétique ?; ii/ du fait de son inconvénient majeur, l'intermittence, pouvons-nous fournir une architecture optimale d'un système basé sur l'énergie solaire associant des systèmes de stockage ?; iii/ quelle est l'efficacité des politiques incitatives mises en œuvre pour accélérer son déploiement ?

Ainsi, dans un premier chapitre, nous analysons la position particulière de l'énergie photovoltaïque dans le mix énergétique. Après un rappel des enjeux des futurs mix énergétiques mondiaux, nous proposons une description sommaire des différentes technologies solaires et de leurs évolutions attendues en termes d'améliorations techniques et de réductions de coûts. Enfin, nous décrivons la croissance très rapide du marché photovoltaïque et de ces conséquences à la fois sur le mix électrique et sur le secteur industriel.

Dans le deuxième chapitre, nous nous intéressons à la problématique de l'intégration de cette énergie intermittente dans le mix électrique, en développant une méthodologie d'évaluation multicritère ainsi qu'un outil d'optimisation multicritère sous contraintes qui permet de faire des simulations d'un système composé de panneaux photovoltaïques et de technologies de stockage. Des cas d'applications sur le cas réel du Cirque de Mafate (L'île de la Réunion, France) sont présentés pour illustrer l'intérêt de la méthode.

Enfin, dans le troisième chapitre, nous questionnons l'efficacité de différentes politiques de soutien aux technologies photovoltaïques dans les pays les plus pertinents. Nous examinons plus particulièrement la corrélation entre la puissance installée, l'argent public dépensé, ainsi que les prix de l'électricité.

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List of abbreviations

ARER: *Agence Régionale de l'Énergie de la Réunion* – Regional agency for energy in *La Réunion* island

CEA: *Commissariat à l'Énergie Atomique et aux Énergies Alternatives* - French Alternative Energies and Atomic Energy Commission

CO₂: carbon dioxide

CRE: *Commission de Régulation de l'Énergie* – French Energy Regulation Commission

CSPE: *Contribution au Service Public de l'Électricité* – French public electricity contribution

DC: direct-current

DoE: US Department of Energy

DTBH: *Département des Technologies Biomasse et Hydrogène* – CEA Hydrogen and Biomass Department

EDELVEISS project: *Évaluation avant Démonstrations Expérimentales en Lignes de la Valorisation de la production Électrique Intermittente par les Systèmes de Stockage* – Evaluation before experimental testing of the valorisation of the intermittent electrical production thanks to energy storage devices

EDF: Electricité de France

EEG law: *Erneuerbare Energien Gesetz* – German Renewable Energy Sources Act

EPIA: European Photovoltaic Industry Association

ETP: Energy Technology Perspective

EU: European

EU ETS: European Emissions Trading System

FIT: feed-in tariff

GDP: gross domestic product

GHG: Greenhouse gas

HDI: Human Development Index

HIT: Heterojunction with Intrinsic Thin layer

IEA: International Energy Agency

INES: *Institut National de l'Énergie Solaire* – French National institute for solar energy

IPCC: Intergovernmental Panel on Climate Change

I-tésé: *Institut de technico-économie des systèmes énergétiques* – CEA Institute for techno-economics of energy systems

LGI: Laboratoire de Génie Industriel

LGLS: *Laboratoire de Génie Logiciel et Simulation* – CEA Laboratory of software engineering and simulation

METI: Ministry of Economy, Trade, and Industry in Japan

MOMuS: *Modélisation et Optimisation MULTicritère du Stockage d'énergie* - Multicriteria modeling and optimization of energy storage

NEF: New Energy Foundation in Japan

NREL: US National Renewable Energy Laboratory

PER: *Plan de Energías Renovables en España* – Plan for renewable energies in Spain

PMMP: *Prix de Marché Moyen Pondéré* - weighted average market price

PPI: Programmation Pluriannuelle des Investissements – French multiannual programming of electric and gas investments

PV: photovoltaic

RES: Renewable Energy Sources

RTE: *Réseau de Transport d'Electricité* in French– French Transmission System Operator

UNFCCC: United Nations Framework Convention on Climate Change

VAT: value added tax

WEO: World Energy Outlook

Wp: Watt peak

Nomenclature

$C_{bat,N,ref}$: Standard nominal capacity [A.h]

$C_{bat,N}$: nominal capacity [A.h]

C_i : cost of investment [€]

C_o : cost of overheads and maintenance [€]

c-Si: single-crystal silicon

dod : depth of discharge [%]

GH_2 : gaseous hydrogen

H_2 : hydrogen

i : current [A]

ig : gassing current [A]

I_{ref} : Standard nominal current [A]

kWh: kilo-watt.hour

mc-Si: multi-crystalline silicon

N : Peukert's constant

Ni-Cd: Nickel-cadmium battery

NOCT: nominal operating cell temperature [K]

P : produced energy [W.h]

P_{max}^0 : standard peak power of a module [W]

Pb-A: lead-acid battery

PEMFC: proton exchange membrane fuel cell

P_{PV} : electrical production of a PV panel [W]

q_{bat} : battery state of charge [%]

q_{bat} : capacity of the battery [A.h]

R_{int} : internal resistance [Ω]

S_{max} : parameter defining the limited electric power that can be exchanged with the electric system [W]

soc : state of charge [%]

t : considered year

T_c : temperature of the cell [K]

TC : total levelized cost

T_{Cref} : temperature of the cell in standard conditions [K]

T_e : time of operation [year]

T_{ext} : outside temperature [K]

T_i : time of investment [year]

u : voltage [V]

U_{co} : battery output voltage [V]

μ_{pmax} : the temperature coefficient [%/K]

τ : discount rate [%]

ξ : solar irradiance [$\text{W}\cdot\text{m}^{-2}$]

ξ_{ref} : solar irradiance in standard conditions [$\text{W}\cdot\text{m}^{-2}$]

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Foreword

The present dissertation encompasses my research activities in the context of my activities in the field of techno-economics of energy systems in the institute I-tésé (Institut de technico-économie des systèmes énergétiques - Institute for techno-economics of energy systems) of the CEA. This work was also improved thanks to the fruitful environment of the LGI Laboratory (Laboratoire de Génie Industriel) of the Ecole Centrale Paris.

These research activities were originally devoted to technical propositions dealing with renewable intermittent energy coupled with storage devices. It appeared progressively that it was also necessary to widen our approach to other topics including economic issues and energy policy. In that sense, this work is intrinsically multidisciplinary and required to join abilities of different experts in mathematical modelling, computer science, technical engineering and economics, as it will be highlighted throughout this dissertation.

General introduction

Energy has undoubtedly played an important role in human development and continues to do so.

Thus, W. Fred Cottrell wrote “The energy available to man limits what he can do, and influences what he will do” [Cottrell, 1995 & 2009]. According to some historians [de Lumley, 2006; Goudsblom, 1987], the link between energy and human development is correlated to the domestication of the fire about four hundred thousand years ago. Access to energy has first allowed satisfying basic needs, such as heating or cooking. The energy applications have gradually diversified, thus developing agriculture and industry, allowing people and goods to move on thousands of miles away, offering access to drinking water, health and education for instance. However, Carbonnier and Grinevald caution us about “applying a much debated evolutionary paradigm” [Carbonnier & Grinevald, 2011], since they think that “analyzing the relationship between the gradual understanding of how to exploit the various sources of energy and the development of civilization is eclipsing in the past the diversity of societies and civilisations” [Cottrell, 1955; Cipolla, 1962 *in* Carbonnier & Grinevald, 2011]. Indeed, this strong relationship between energy and human development seems to be more recent. It dates from the industrial revolution of the nineteenth century and is linked to the appearance of the internal combustion engine [Grinevald, 1990]. The link between energy and the gross domestic product (GDP) is strongly debated among the economists as reviewed by Chontanawat & *al.* [Chontanawat & *al.*, 2008]. On the one hand, it is argued that energy is “a vital and necessary input along with other factors of production (such as labor and capital)” and as a consequence is a “limiting factor to economic growth” [Ghali & El-Sakka, 2004, *in* Chontanawat & *al.*, 2008] whereas on the other hand it is argued that “the cost of energy is a very small proportion of GDP” and has no impact on the economic growth. Nevertheless, nowadays the link between energy and the human development is clearly shown. In order to evaluate it, the Human Development Index (HDI) is frequently used. It was created by the economist Mahub ul Haq [UNDP, 1991; Haq, 1995], in order to measure the socio-economic progress using more than the only criterion of income measured by the GDP. “The HDI has three key components: longevity, knowledge and income”. Haq has also explained clearly that these criteria must be adapted (in terms of fields covered or in terms of number of criteria) with the evolution of the society. Thus, Sagar and Najam think that HDI is open to accusation of not taking environmental issues into consideration [Sagar & Najam, 1998]. They even propose some modification of the index. The weaknesses of the HDI have also been pointed out by Ranis & *al.* [Ranis, Stewart & Samman, 2006] and they proposed to complete the analyses of the human development by other indicators such as the under-five mortality rates for instance. In the latest publication of the United Nations Development Program, “Human Development Report 2013”, the

studies are led using not only the HDI but also the Inequality-adjusted HDI, the Gender Inequality Index, the Multidimensional Poverty Index, Innovation and technology Index or Environment Index for instance [UNDP, 2013].

Anyway, the relation between the Human Development Index and the energy used per capita can be observed for the 2008 values on Figure 1 [Goldemberg, 2012]. It seems that we can approximate the relation between the energy consumed and the HDI by a logarithmic curve. Thus, for the developing countries, the access to energy allows to improve the quality of living, whereas for developed countries, for the same standard of living, there are strong differences in the quantity of energy consumed and as a consequence strong differences of their impact on the environment.

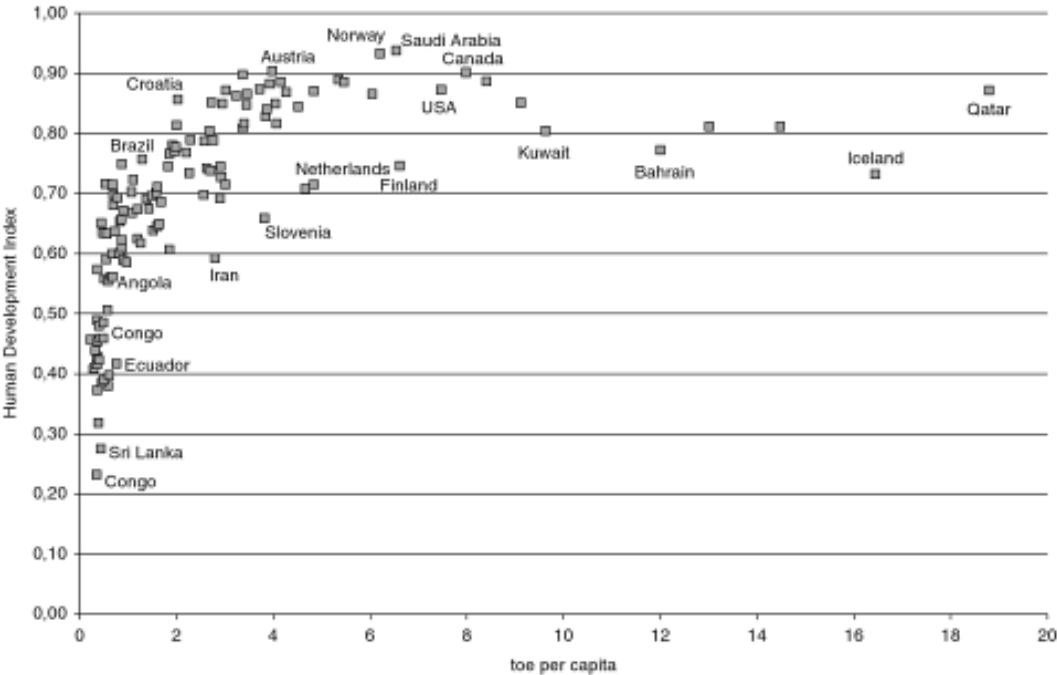


Figure 1: Relation between the Human Development Index and per capita energy use (2008) from [Goldemberg, 2012]

Furthermore, **the global energy mix is strongly based on fossil fuels**, since the modern economic development is mainly based on mineral resources and not on renewables (see Figure 2). This is due to the extraordinary properties of oil which is present everywhere in our societies [Amyx, J. W. & al., 1960] (For example, oil is liquid and easy to used, it has a very high energy density and a very high bulk density, and of course it is not an expensive energy so far).

Thus, in 2012, more than 80% of the global primary energy demand was met by fossil fuels [CAS, 2012]. Oil provides 33% of the world energy needs, followed by coal (22%) and gas (21%). The nuclear energy covers 6% of primary energy needs. Finally, the renewable energy sources represent 13% of the global supply with a strong weight for hydraulics (10%).

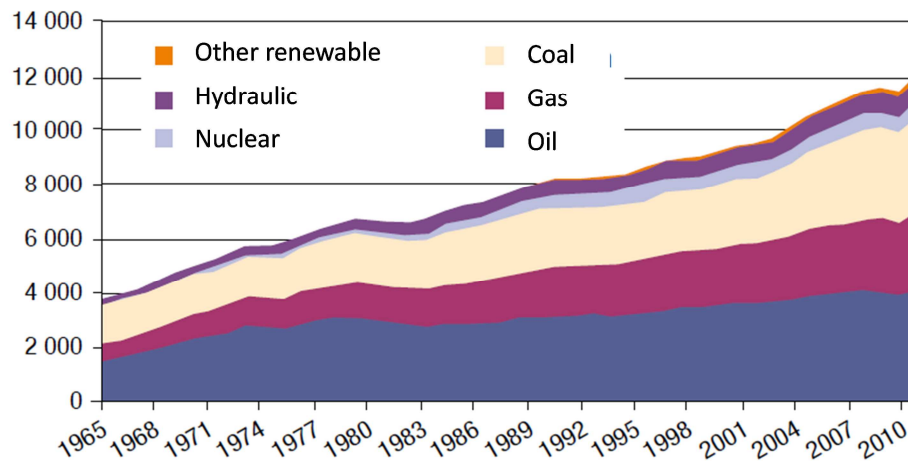


Figure 2: Global primary energy consumption in Mtep [BP, 2011 in CAS, 2012]

There are some disparities in the regional distribution. According to British Petroleum [BP, 2012], in 2011 “the Asia Pacific region [was] the world’s largest energy consumer, accounting for 39.1% of global energy consumption and 68.6% of global coal consumption”. To first order, we can say that Europe & Eurasia is the leading region for consumption of natural gas, nuclear power, and renewables, and that oil is the dominant fuel in all other regions. Disparities also exist in terms of growth.

One of the consequences of this massive use of fossil fuels is the increase of the environmental degradation and the interferences with the climate system of the biosphere as it has especially been described by the Intergovernmental panel on climate change [Pachauri & *al.*, 2008; Bates. & *al.*, 2008; Gitay & *al.*, 2002]. According to the IPCC, no serious policy to reduce CO₂ emissions would lead to an increase in global temperature between 1.1 °C to 6.4 °C by 2100 depending on the scenario. The average sea level would rise of 18-59 cm (effects of melting ice and expansion of the oceans). The precipitation patterns would also be affected (more droughts in some regions and more rains in other ones).

For some years now there has been an increasing interest in the problem of the release of greenhouse gases (GHG) and air pollutants. It began with the Summit of Rio in 1992, during which the *United Nations Framework Convention on Climate Change (UNFCCC)* was adopted. The first strong policy measures against the CO₂ emissions were signed in 1998 with the Kyoto protocol and consisted in the establishment of targets of emission reductions in relation to those of 1990 [Protocol, 1997]. The aim is to limit the overall increase in global temperature to 2 degrees. At the European level, there is also a proactive political program. Three key objectives for 2020, known as the “20-20-20” targets, have been defined through the “energy package”, a set of binding legislation which aims to ensure that the European Union meets its ambitious climate and energy targets for

2020 [CEC, 2008a; CEC, 2008b; CEC, 2008c; CEC, 2008d; European Commission, 2009]. Thus, in 2020, there should be a reduction in the European Union of 20% in GHG emissions compared to the 1990 level, the share of energy consumed produced from renewable energy should raise of 20% (depending on the situation of each member State, between 10% for Malta until 49% for Sweden) and an improvement of energy efficiency of 20% should occur. More recently, the European Commission even studied the possibility to increase its emission reduction to 30% by 2020 [European Commission, 2010]. Along with these directives, a European emissions trading system “cap and trade” (EU ETS) has been set in order to reduce the industrial GHG emission cost-effectively [European Commission, 2003; European Commission, 2004; European Commission, 2008; European Commission, 2009]. The EU ETS was launched on 1 January 2005 and covers over 11,000 heavy energy-using installations (power stations and industrial plants) in 31 countries, as well as airlines (flights to and from the EU and the three EEA-EFTA¹ States). This economic tool does still make no consensus. Indeed, it is reproached some disparities in quota allocations: in some cases, there were over allocations not allowing any reduction in CO₂ and in some other cases, the allocations were too small, particularly in the electricity sector, generating very high prices and negative distributional effects [Vlachou, 2009]. The problem of the electricity sector has also been studied by Delarue & al., in terms of amount of necessary abatement [Delarue & al., 2008]. More recently, the economic downturn has resulted in the sale of a large volume of quotas, making the price of a ton of CO₂ collapse [Vlachou, 2010]. The European Power Exchange (EEX) spot prices were €3.20/tCO₂ on the 23rd of May 2013, which is of course too low to be dissuasive.

Notwithstanding these criticisms, it is important to aim for a sustainable development. According to Lord Stern [Stern, 2006] "any investment made now to reduce CO₂ emissions will be paid back in the future as the external costs of fossil fuel consumption will be avoided".

So, the energetic issues are on the top of the political agenda in many countries, for environmental reasons, for its driving role in all the economic sectors, as well as for the energetic independency concerns. This problematic is stressed by the increasing weight of renewable intermittent power sources in the global mix. In particular, due to its high potential and the strong national policy support it benefited, solar photovoltaic energy is now a key player in the world energy mutation and the way it is integrated into the global mix should be carefully performed.

¹The European Economic Area (EEA) unites the EU Member States and the three EEA EFTA (European Free Trade Association) States (Iceland, Liechtenstein, and Norway) into an Internal Market governed by the same basic rules.

To deeply understand the way solar energy can penetrate and transform the forthcoming energy framework, we adopted a three-level strategy with a multidisciplinary approach to provide some answers to the following questions: i/ how can we situate the photovoltaic power role in future energy mixes?; ii/ due to its main drawback, intermittency, could we provide an optimal design of a system combining storage devices?; iii/ what is the efficiency of the incentive policies that are or have been implemented to accelerate its deployment?

That is why, in a first chapter, the peculiar position of the solar photovoltaic energy in the energy mix is analyzed. After recalling the general issue of future global energetic mixes, we propose a brief description of the different photovoltaic technologies and their promising evolutions in terms of technical improvements and cost reductions. Then, we describe the fast growing photovoltaic market and its consequences both on the electricity mix and the industry sector.

In the second chapter we investigate the issue of integrating such an intermittent energy in the electricity mix, by developing a multicriteria evaluation methodology and a multicriteria under constraint optimization tool which simulates a system composed of photovoltaic panels and storage devices. Applications on a real case in the *Cirque de Mafate (L'île de la Réunion, France)* are presented to illustrate the interest of our method.

Finally, in chapter three, we question the efficiency of different public support policies to the photovoltaic technologies in the most relevant countries. We focus on correlating the installed power capacity with the spent public money and the electricity prices.

The findings which correspond to this work have been published through eleven references including four publications in international journals with referees [Avril & al, 2010; Avril & al, 2011; Avril & al, 2012a; Avril & al, 2012b].

Chapter One: The solar photovoltaic energy in the global energy mix

1. Introduction of the chapter one

As exposed in the general introduction, energy is crucial for human development and well-being. However, the global energy mix is still mainly based on fossil fuels and generates a lot of GHG emissions. About 65% of the emissions in the World are due to the use and production of energy [IAE, 2008]. When focusing on OECD countries or the European Union, this percentage is higher, about 80% [Marrero, 2010]. By analyzing a panel data set of 24 European countries between 1990 and 2006, Marrero [Marrero, 2010] highlighted that the impact of energy consumption on emissions would depend on the primary energy mix and on the final use of this energy, which is coherent with the theory developed by Ang by analyzing France and Malaysia data [Ang, 2007; Ang, 2008]. So, to reduce the GHG emissions due to the global energy mix, there are two main actions to launch in parallel. On the one hand, it is very important to improve the way energy is used, *i.e.*, to continue the efficiency gains in the industry sector, the transportation sector and in the buildings, as well as energy savings. On the other hand, it is important to introduce more renewable energies in the primary energy mix.

The aim of this first chapter is to focus on the role that can be played by the solar photovoltaic energy in the global energy mix.

The findings which correspond to this chapter have been published through one reference [Avril & al, 2014].

Thus, in a first part, the issue of a sustainable mix with an important part for renewable energies, including solar photovoltaics, is raised, and reinforced by the necessary change of uses (for instance, converting fossil mobility into electric mobility). In a second part, we are focusing on the photovoltaic technology potentials. After briefly explaining the photovoltaic effect, we are presenting the three generations of cells as described by Green [Green, 2003] as well as the emerging and future PV technologies. Then, we describe the fast growing photovoltaic market these past ten years and its consequences both on the electricity mix and the industry sector.

2. About the necessity for the energy mix to become sustainable

The challenges of the global energy mix are daunting: the security of energy supply, fighting against climate change and access to energy for all at an affordable cost. This, in a context of very high population growth (+1.2%/yr according to [INED, 2013]), global financial and economic crisis of great magnitude, with economic uncertainties which have never been stronger. We can advance some figures. There are now over 7 billion people in the world, with growing energy needs. The primary energy consumed worldwide is more than 80% fossil, raising both the issues of resource depletion and GHG emissions. In 2011, 20% of the population still has no access to electricity, while according to the International Energy Agency it would suffice to increase by 5% global annual investment in the electricity sector for that in 2030 the whole population has access to electricity, knowing that living without electricity reduces life expectancy by two. Emissions of GHG are rising faster today than they have ever done, due mainly to the use of fossil fuels and, to a lesser extent, changes in land use. For example, the carbon dioxide from the burning of fossil fuels increased from 6.4 Gt per year in the years 90 to 7.2 Gt of carbon per year for the period 2000-2005, an increase of more than 10%.

According to Carbonnier & Grinevald [Carbonnier & Grinevald, 2011], "since the 1970s debate has been raging between the optimists who trust market forces and man's capacity for innovation and technological ingenuity to overcome these obstacles, on the one hand, and the pessimists (who nonetheless would describe themselves as realists) who believe that there is an urgent need to take seriously the dual threat of post-peak oil and global warming, on the other. The pessimists appeal to us to rectify the excesses of the consumer society, which are threatening the planet's ecological balance. On an academic level, they campaign for an epistemological paradigm shift in economics to take the relevant insights from natural sciences into consideration. This epistemological battle pits short-term political and economic visions and imperatives against the long-term ecological perspectives." These two visions are as important today as ever. It can be observed through the numerous prospective scenarios of the energy mix.

Three kinds of scenarios are often used to propose a vision of the future. "Business As Usual" scenarios try to give the most probable future vision. Scenarios called "exploratory" or "story-telling" illustrate contrasting trends from the present system. For such scenarios are often used simulation models of the energy system from mathematical models that provide technical and economic coherence (bottom-up, partial equilibrium models), econometric or macroeconomic (top-down general equilibrium models). We can then specify the role of prices (formation mechanism, impact of taxes and economic policies such as ETS impact on consumption). And finally, scenarios called "back casting", "normative" or teleology emphasize one or more goals in the future and offer paths leading

to them. These scenarios therefore reveal wished future. It is then often used optimization models (sector for the bottom-up, and optimal for the top-down control) to obtain optima in terms of objective trajectories.

The most known scenarios are those of the International Energy Agency (IEA). Its most famous publications are the World Energy Outlook (WEO) (Cf. Figure 3) and the Energy Technology Perspective (ETP). In the World Energy Outlook 2012 [IEA, 2012], four scenarios are considered. Their conclusions are rather pessimistic. Indeed, “taking all new developments and policies into account, the world is still failing to put the global energy system onto a more sustainable path”. Their central scenario is the one named “New Policies Scenario”. “Fossil fuels remain the principal sources of energy worldwide, though renewables grow rapidly. Demand for oil, gas and coal grows in absolute terms through 2035, but their combined share of the global energy mix falls from 81% to 75% during that period. The unlocking of unconventional resources portends a very bright future for natural gas, which nearly overtakes coal in the primary energy supply mix by 2035. Nuclear power maintains a 12% share of electricity generation, a downward revision from previous projections in light of additional policy changes in several countries prompted by the accident at Fukushima Daiichi. Renewable deployment is driven by incentives, falling costs, rising fossil fuel prices and, in some cases, carbon pricing: their share of electricity generation grows from 20% in 2010 to 31% by 2035.”

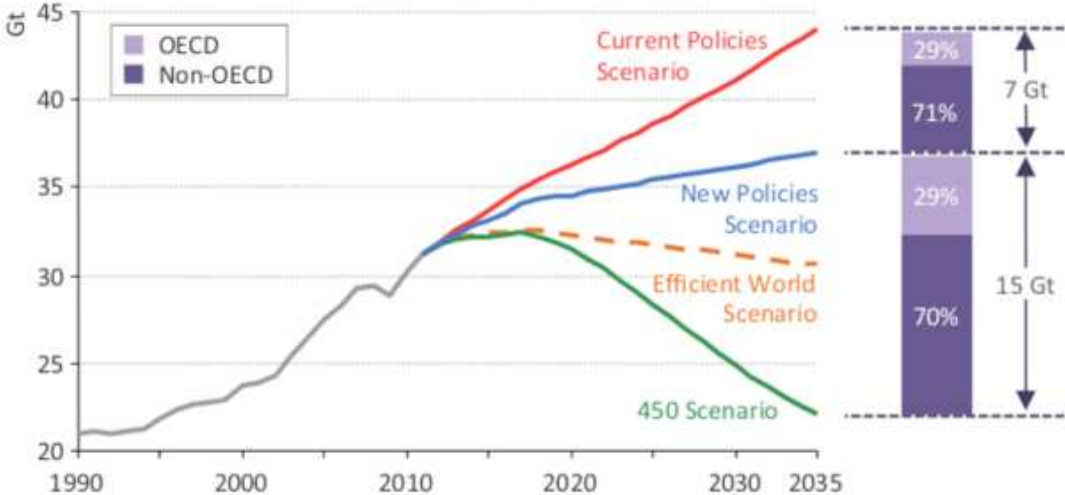


Figure 3: Global energy-related CO₂ emissions by scenario (source WEO 2012 [IEA, 2012])

However, numerous other scenarios exist. Their publication is often linked to political debates. Thus, in France, preceding the publication of the Energies 2050 report [Percebois & Mandil, 2012] which was aiming at preparing the new law on multiannual programming of electric and gas investments (PPI - Programmation Pluriannuelle des Investissements), numerous energetic or electric scenarios appeared. The most famous were “Negatep” elaborated by “Sauvons le Climat” [Acket & Bacher,

2012], "Negawatt" [Salomon & al., 2005], the Enerdata scenarios established for the Department of Climate and Energy at the Ministry of Ecology, Energy, Sustainable Development and the Sea (DGEC, *Direction Générale de l'Énergie et du Climat*), the one of the French Union of Electricity (UFE) [Boitier & al., 2012], the one from the transmission system operator (RTE), the one from Global Chance [Dessus & Girard, 2006], an association which desires to stop the use of nuclear energy, the one from the nuclear industrial AREVA or the one from the CEA, the French Alternative Energies and Atomic Energy Commission, a research organism in low CO₂ emissions energies [CEA, 2012]. The comparison of these scenarios has highlighted three major lessons (Figure 4). Demand is very varied, and energy and electricity consumption can either increase or decrease. Structurally, the mixes are very different, with the relative shares of renewables and nuclear highly variable (in order to respond to a high demand, nuclear power is highly used). Finally, the development of renewable energy tends to increase the use of electricity.

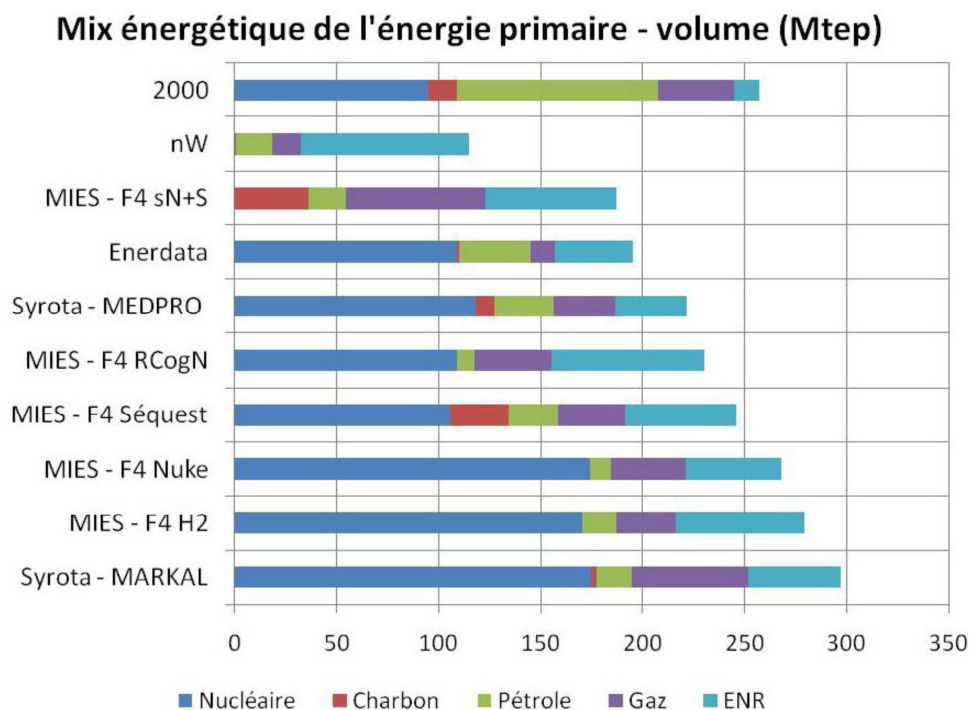


Figure 4: French mix in 2050 according to various studies, with "factor 4" constraints

Currently, the national debate on energetic transition carried out by the French Government has had the same effect. The synthesis published in July 2013 showed 15 major challenges, aiming to make an ambitious energy transition and for all, to put energy efficiency at the service of competitiveness, to provide an energy mix emitting little GHG, secure, diverse, balanced and cost competitive, and highlighting the drivers, including the financing, the regulatory framework and the training [MEDDE, 2013].

All these considerations let us think that whatever the different policies will be, the renewable energies will play a crucial role in the next years. We decided to focus our work on photovoltaic energy and the conditions to foster its development. Next section aims at presenting the photovoltaic technology potentials.

3. Photovoltaic technology: state of the art and potentials

3.1. The photovoltaic effect

The PV effect consists in the conversion of radiative energy (photonic flux) into electricity (electronic flux). The periodic sheet of atoms within a solid implies two possible energy levels of the electrons: the valence band and the conduction band. These two energy levels are separated by an energy gap depending on the nature of the material of the PV cell. When striking a cell, the photonic flux may impart enough energy to some electrons to raise their energy and thus free them. In fact, depending on their energy level, the incoming photons are either reflected, absorbed or transmitted. Only the absorbed photons, whose energy level overcomes the energy gap, can partially break a valence bound and thus generate an electron-hole pair that may be mobile. Note that the exceeding energy quickly fades out by dissipating within the crystal network. Due to the necessity to have an important electric field when generating an excited electron and its concomitant hole, the conductive materials should be avoided. Moreover, non-conductive materials cannot be used to drive a significant current in the external circuit. As a result, the semi-conductive materials are the best candidates to ensure the PV effect.

The electrical power consumed by the load is the product of the electrical current supplied by the cell and the voltage across it. According to the solar radiations and the classical semi-conducting materials band gap of 1 and 1.5 eV, each cell can supply current at a voltage from 0 V to a maximum in the 0.5-1.0 V range.

3.2. Three generations of PV cell technologies

Current technologies and possible future options have been categorized from current first-generation to future third-generation technologies [Green, 2003]. Performances differ from one technology to another, depending on the different maturities (Cf. Figure 5).

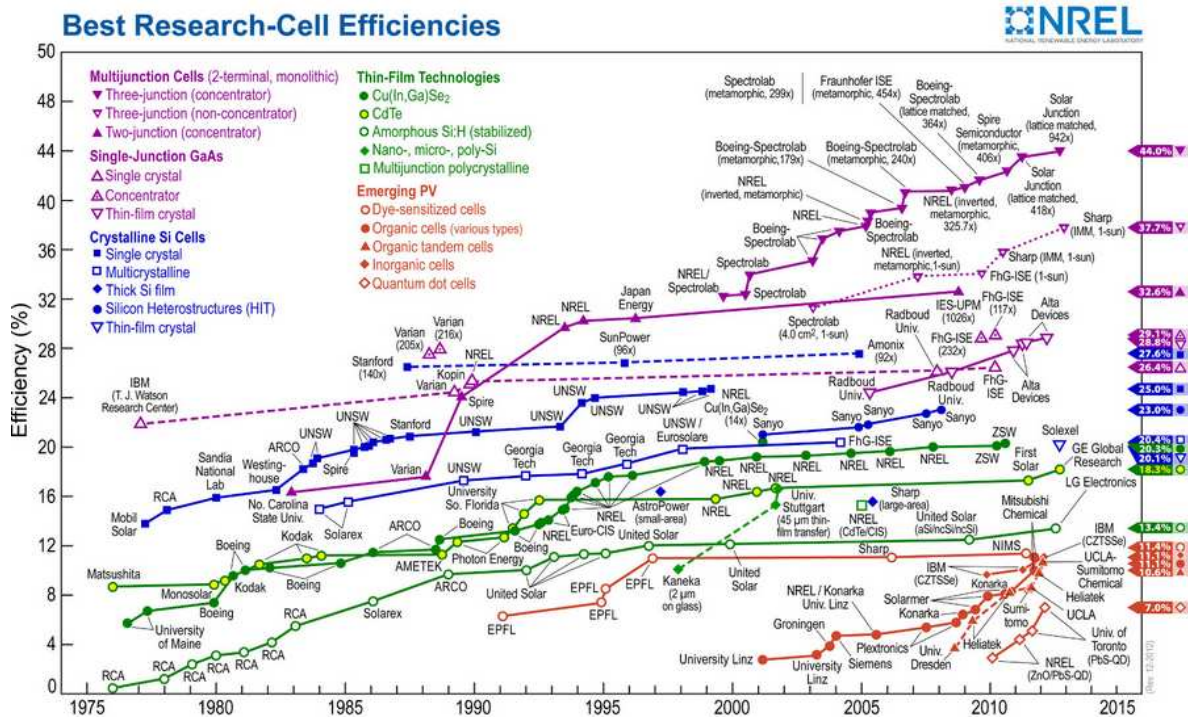


Figure 5: Best research-cell efficiency from 1974 to 2012 [NREL, 2013]

3.2.1. First Generation (1G)

The current PV market consists of a range of technologies including wafer-based silicon and a variety of thin-film technologies. More precisely, the first generation of solar cells based on single-junction mono- and multi-crystalline silicon wafers currently account for 90% of PV production. Originally built using single-crystal wafer silicon (c-Si) and grounded in the integrated circuit industry, silicon wafer-based PV has the advantage of rather high conversion efficiency and identical processes to that used in the much larger microelectronic industry, thus benefiting from the corresponding economies of scale [Green, 2000].

More precisely, commercial single-crystal wafer silicon efficiencies range between 18–21% whereas the cheaper multi-crystalline silicon devices (mc-Si) with lower cell efficiencies (around 13–14%) represent 63% of the world market [Bagnall & Boreland, 2008]. The main drawbacks of these first generation technologies consist in the large amounts of silicon required and especially the high costs for their purification [Grau & al., 2012]. So reduction of wafer thickness offers cost-reduction potential.

3.2.2. Second Generation (2G)

To reduce the cost-to-power ratio of the PV technology, the next step consists in removing the unnecessary material from the cost equation by using thin-film devices. In this approach, thin layers

of semiconductor material are deposited onto a supporting substrate, or superstrate, such as a large sheet of glass. This typically requires a 100 to 1000 times thinner slice than the thickness of a silicon wafer of the first generation. Reduced material use with associated reduced costs is a key advantage. Another is that the unit of production, instead of being a relatively small silicon wafer, becomes much larger, for example, as large as a conveniently handled sheet of glass might be. This also reduces manufacturing costs.

Silicon is one of the few semiconductors inexpensive enough to be used to make solar cells from self-supporting wafers. However, in thin-film configuration, due to the reduced material requirements, virtually any semiconductor can be used. Indeed, semiconductors can be formed not only by elemental atoms such as silicon, but also from compounds and alloys involving multiple elements, there are plenty of semiconductors from which to choose [Berger, 1997]. Single junction amorphous (uncrystallized) silicon is the most popular thin film technology with cell efficiencies of 5-7%. However, it is prone to degradation [Parida & *al.*, 2011]. Thus, the main drawback of thin technology devices is their lower efficiency inducing higher surface area requirements to provide the same amount of energy. Other difficulties for non-silicon technologies exist: some input materials are rare elements (tellurium Te) whereas others can represent a hazard for human health (cadmium Cd).

3.2.3. Third Generation (3G)

In the wake of the 2G thin-film technologies, due to the reducing of active material cost, the low cost substrate tends to become the cost limiting factor and improved efficiencies of the solar devices are required to pursue the cost-to-power ratio reduction trend.

That is why the third generation of PV technologies consists in using multiple junctions [Yoshimi, 2003; Green, 2006]. Here, a stack of different solar cells with various bandgaps is able to use the entire solar spectrum. Due to their quite expensive cost, these technologies are nowadays only used in “niche” applications such as satellite power generation [Brown and Wu, 2009]. Note that these solar cells are combined with concentration optics and therefore require frames that can be adjusted to follow the direction of the sun.

3.3. Emerging and future PV technologies

If some efforts are made to improve the material composing the thin film solar cells [Mainz & Klenk, 2007], the next step in the solar technologies should be accompanied by new ideas. In that viewpoint, several innovative concepts have been proposed over the past twenty years to reduce the

costs or increase the solar device efficiencies. For instance, we can mention the use of polymer semi-conducting systems [Peumans & *al.*, 2003; Hadipour & *al.*, 2008], quantum wells, wires and dots to enhance light absorption [Barnham & Duggan, 1990], the use of impurity levels [Corkish & Green, 1993], the use of impact ionization to better collect the kinetic energy of carriers [Kolodinski & *al.*, 1993; Landsberg & *al.*, 1993], the conception of dye-sensitized cells [Gratzel, 2001], the development of new meta-materials such as nano-structured glasses or silicons [Wohlgemuth & *al.*, 2005; Boden & Bagnall, 2006; Vukusic & Sambles, 2003], plasmonic devices [Mulvaney, 2001].

Notwithstanding the attractiveness of these projects on paper, they still have everything to prove in practice and all these technologies need more time to get mature.

Finally, a revolutionary new approach suggested by [Bailey, 1972] focuses on the wave nature of light. It was suggested that broadband rectifying antennas could be used for solar to direct-current (DC) conversion. These “rectennas” would not face the fundamental issue of a semiconductor’s bandgap limiting conversion efficiency. Rectennas for solar conversion would have dimensions on the order of the wavelengths of solar radiation that falls mostly in the sub-micron range [Razykov & *al.*, 2011]. The primary advantage of the antenna approach to solar energy conversion is that conversion would not be bandgap limited, as it is in PV cells. In making this assertion, it is assumed that the process of rectifying high frequency electromagnetic waves will not involve any such lossy quantum effects.

The past, present, and future of rectenna conversion are reviewed by [Goswami & *al.*, 2004].

Two fundamental physical limitations, the skin effect resistance and a very low voltage per antenna element, were identified for the rectenna system.

Over the next 20 years, we can foresee only small improvements in the production efficiencies of 1G silicon technologies. However, we can expect manufacturing, installation and operational cost reductions that will continue to provide reduced cost of solar energy. In the same period, we will witness a change from predominantly 1G production to an era of 2G devices based on thin-film silicon. While these two mainstreams will dominate the commercial PV sector, we expect that we will see increasing use of new and 3G technologies that will enhance the performance or reduce the cost of solar cells. These technologies are very likely to include some multi-junction concepts and constructs based on the emerging fields of optical metamaterials, plasmonics, quantum technology, nanotechnology and polymer semiconductor science.

4. The global PV market: history and trends

In this section, we are describing the global PV market and the activities of economic bodies, with a focus on the period 2000-2013.

4.1. A dynamic market

The photovoltaic market significantly grew these past ten years. The global PV cumulative installed capacity was 102,156 MW at the end of 2012 (it was only 2,235 MW in 2002, which represents almost 50% growth each year during ten years) [EPIA, 2013]. This market has been driven by Europe, mainly for political reasons (to limit the energy dependence and the GHG emissions) and thanks to strong public supports. This point will be further detailed in chapter 3. Thus, Germany is the world's top PV market with 7.6 GW of newly connected systems and a cumulative installed capacity of 32.4 GW at the end of 2012 [IEA-PVPS, 2012]. Then, there is Italy with 16.25 GW (2nd position), the USA with 7.2 GW installed (3rd position) and China and Japan with 7 GW installed each (4th position). France is seventh with 4 GW installed at the end of 2012, 1 GW having been installed in 2012 (Figure 6).

However, we can now observe a slow-down in the capacities installed in Europe (see Figure 7 and Figure 8). According to the European Photovoltaic Industry Association (EPIA), this is due to a stabilization phase after the previous boom. This slow down can also be explained by the fact that this development is expensive especially for the countries which have developed PV thanks to feed-in tariffs (FIT) which generate high prices of electricity which are not appropriate in the actual context of financial and economic crisis.

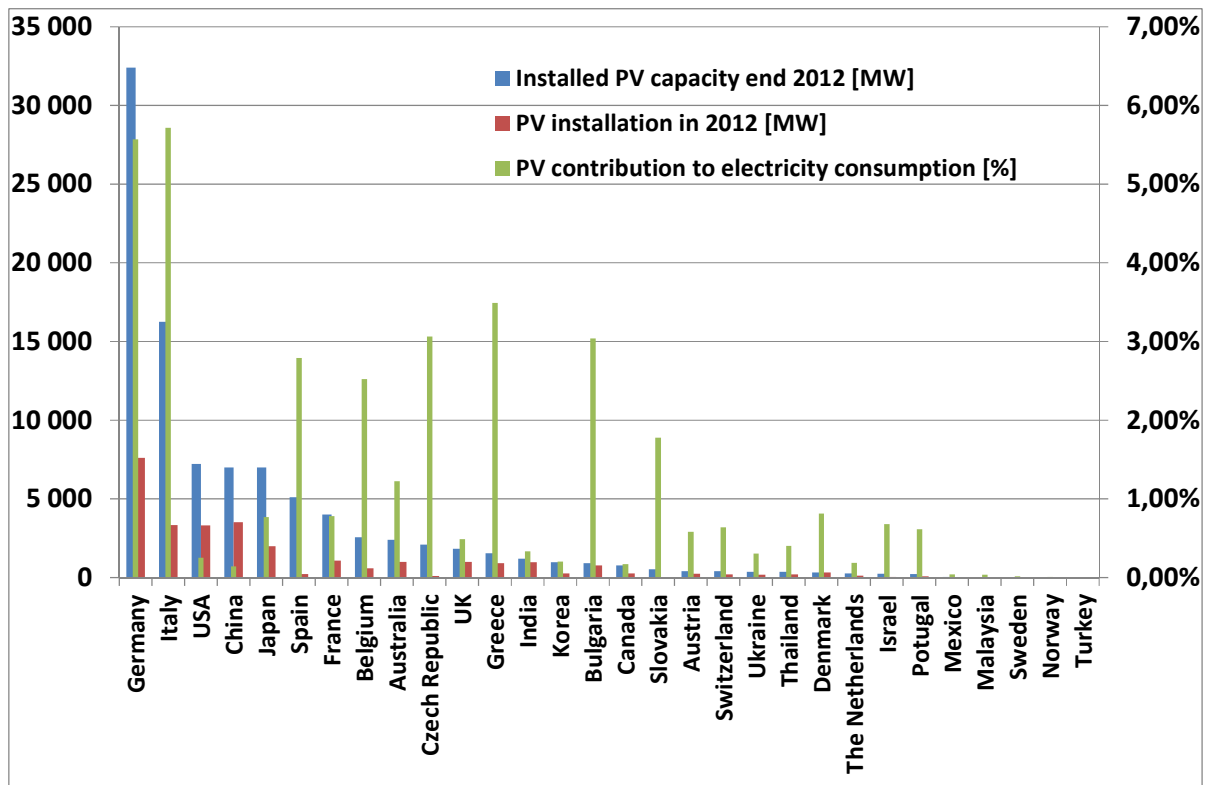
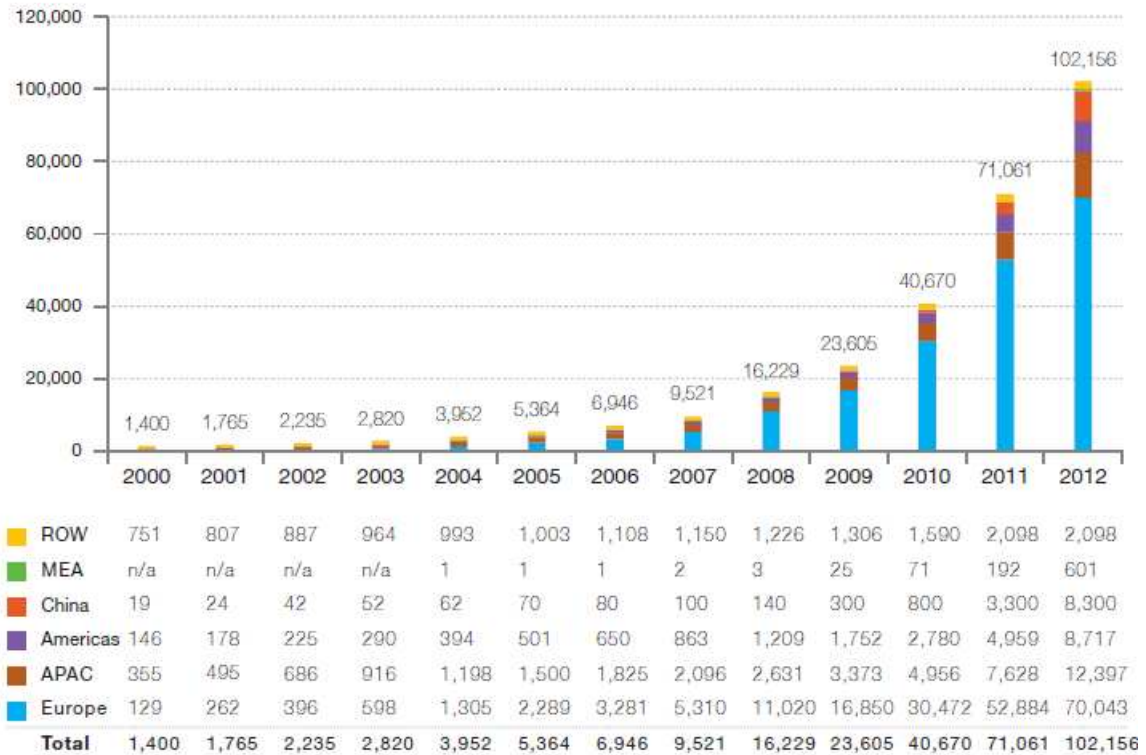
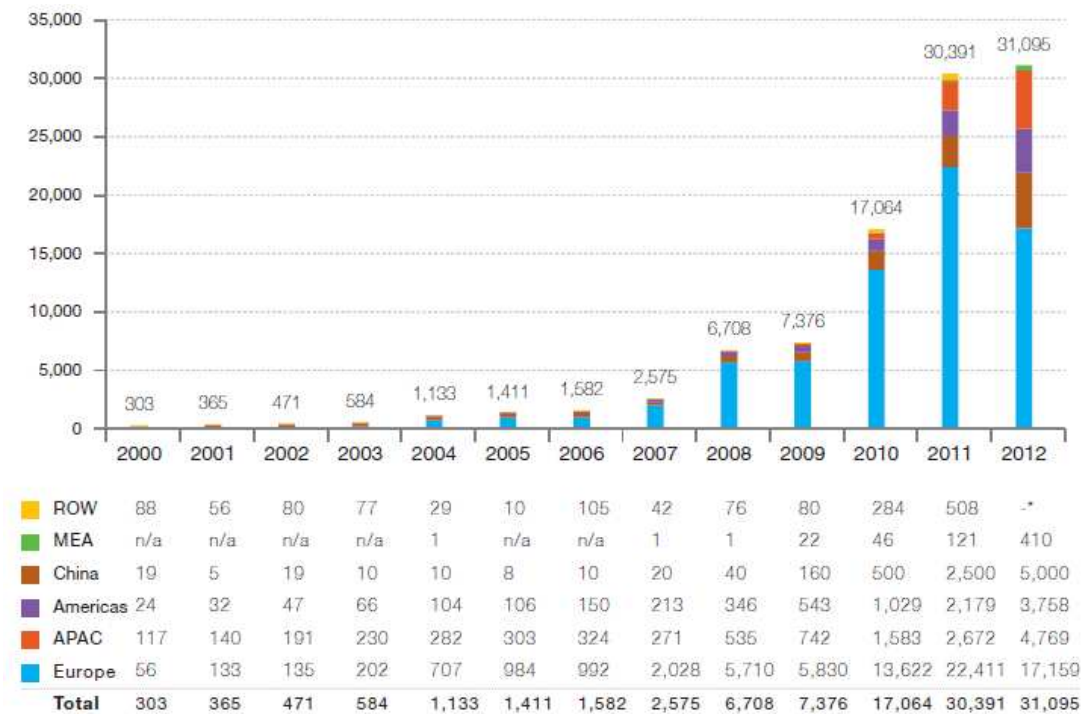


Figure 6: Installed PV capacity at the end of 2012 and PV installation in 2012 in MW (left axis) and PV contribution to electricity consumption in 2012 [%] (right axis) adapted from [IEA-PVPS, 2012]



ROW: Rest of the World. MEA: Middle East and Africa. APAC: Asia Pacific.

Figure 7: Evolution of global PV cumulative installed capacity 2000-2012 (MW) [EPIA, 2013]



* From 2012 onwards, these figures are directly integrated into those of the relevant regions.

Figure 8: Evolution of global PV annual installations 2000-2012 (MW) [EPIA, 2013]

This European slowdown will not affect the global PV market. Indeed, it is counterbalanced by an increase in the countries of the Asia-Pacific region, especially China and Japan (respectively 3.5 GW and 2 GW installed in 2012), and in the USA (3.3 GW installed in 2012).

As a consequence, the perspectives for the global PV market are optimistic. The EPIA considers 2 forecast scenarios of the PV growth over the next five years, the differences between the "business-as-usual" scenario and the "policy-driven" one mainly depend on the "ability of policymakers to maintain market conditions at an acceptable level" in Europe. In 2017, the annual installed capacity would be between 48 and 84 GW depending on the scenario (compared to 31 GW in 2012), and so the cumulative installed capacity would be between 288 and 422 GW (compared to 102 GW in 2012, *i.e.* a tripling or a quadrupling in only five years).

These EPIA forecasts also consider two kinds of PV systems: roof-top and utility-scale systems. In 2012, around 70% of the global annual installations were rooftop systems in terms of power installed (22 GW of roof-top installations against 9 GW for utility-scale systems) with strong differences depending on the country (see Figure 9). The future development being expected in the Sunbelt markets, utility-scale systems will probably grow faster than roof-top ones and only 55% of the new installed systems will be roof-top ones (in terms of power installed).

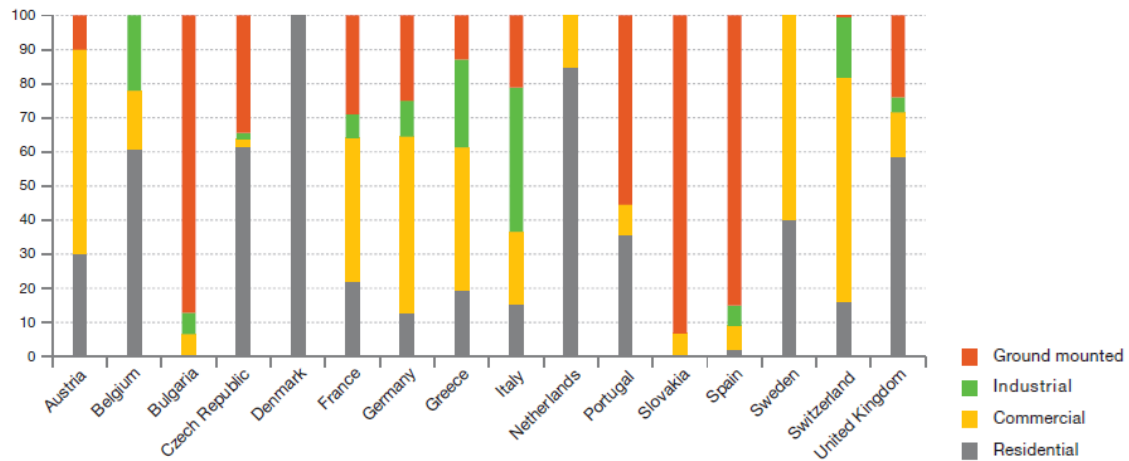


Figure 9: European PV cumulative capacity segmentation by country in 2012 (%) [EPIA, 2013]

4.2. Consequences of the PV growth on the European electricity mix

In this subsection we are focusing on the European mix since this has been the main PV market until now and as a consequence this is where the consequences of the PV growth are the most pronounced.

The major consequence of this high deployment of PV technologies is its impact on the electricity mix. Indeed, whereas new capacities were off-grid systems at the beginning of this deployment, almost all new installed systems are connected to the grid, especially in Europe. This electric production begins to be significant in some countries, representing more than 5% of the annual electricity demand on average for Germany and Italy (see Figure 6 page 32). On the one hand, this is a good point since solar energy is contributing to the way of a sustainable electricity mix; on the other hand, this energy is a fatal energy, it is intermittent or as it is now used to say “non-dispatchable” and as a consequence not always correlated to the electricity demand. This second point may become an issue. Indeed, when this production was not significant, it was easily absorbed by the network and could be injected in priority, the fossil energy and hydraulic power plants adjusting their production. However, there are times when this production is not negligible at all compared to the other means of production (in Germany, the PV maximum instantaneous contribution to electricity consumption in 2012 was 45% [EPIA, 2013]). However, European systems are interconnected; in the case of a high PV production, all the other power plants must decrease their production in order to stabilize the electric system, thereby lowering their load factor and profitability. We even saw negative electricity prices appear (example of the Sunday 16th of June 2013: the EPEXSPOT Intraday Index was minus €68.70/MWh at 2 p.m., the production being of 571 MW for a 100 MW demand [EPEXSPOT, 2013]). The whole system is weakened. Investments are no more profitable, even though it is anticipated capacity requirements in the medium term. In the

context of the European electricity market that will exist in 2014, important discussions are thus carried out to address this problem by introducing capacity market. This implies complex mechanisms; the European Commission wishes one unique capacity mechanism [AEE, 2012], but there would not be an ideal solution for all of Europe, the problems depending of the situation of each region. However it will be important to make sure that the chosen solutions will be compatible at a European level. Another solution consists in shaving-up the peak production of PV.

Whatever the economic mechanisms that will be used, finding profitable technology solutions to the problem of the intermittency of solar photovoltaic will enable its wider deployment. The solutions would certainly be a mix of solutions including economic mechanisms and technological solutions, among which storage technologies would play a role.

Similar consequences could appear on the other continents considering that a strong PV growth is forecast over there.

4.3. Consequences of the PV growth on the global solar industry sector

The PV market has grown very fast and so did the PV revenue. Indeed, according to Clean Edge, a research and advisory firm devoted to the clean-tech sector [Statista, 2013], the global solar PV manufacturing market grew from 2.5 billion US dollars in 2000 to 91.6 billion US dollars in 2011. This leads to an average annual growth around 40%. There has been a slow-down in 2012 with a market of 79.7 billion US dollars. However, Clean Edge forecasts a value of 123.6 in 2022 [Clean Edge, 2013]. It still represents an average annual growth around 4.5% for the ten next years.

So, the PV market, which is very profitable and fast growing, has attracted many players. According to the EPIA [EPIA, 2013], they “entered the business ramping up very quickly their production capacity to increase their share of what in most cases was wrongly forecast, volatile and policy-driven PV demand”. This led to an overcapacity of production. Thus, “despite some cases of specific material/component shortage that have been seen in the last three years, module production capacity was in between 150-230% higher than annual global installations.” This dissymmetry between supply and demand capacities is accentuated by regional differences.

Thus, since 2001 Europe has no longer produced enough for its own needs, and since 2004 Europe imported more than it produced (see Figure 10), mainly from Asian countries. We can particularly observe a domination of China in exporting PV modules from 2008. It can have been done not only with high capacities, but also with very low prices.

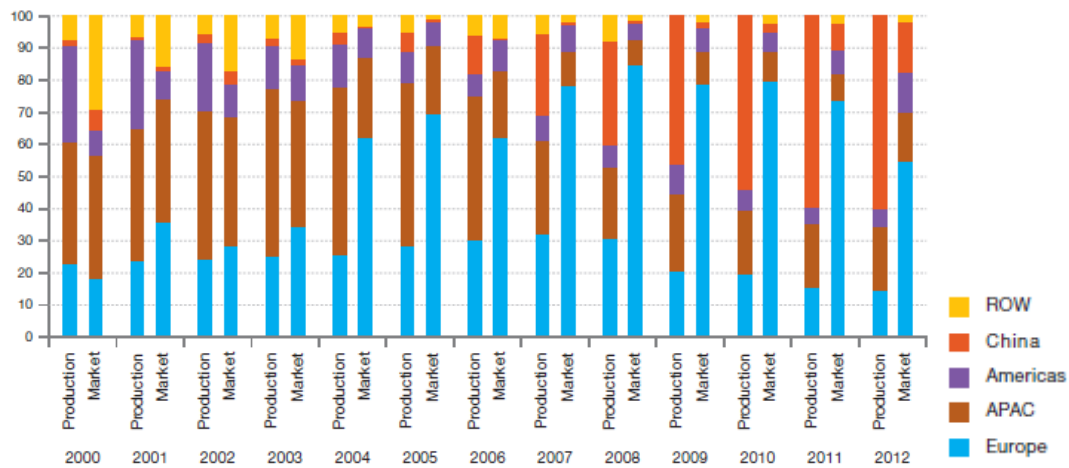


Figure 10: Historical PV market versus production by region (%) [EPIA, 2013]

Sale prices of Chinese modules being very low compared to other countries, suspicion of dumping was quickly attached to China. History recently showed that these suspicions were substantiated. Indeed, given the difficulties faced by their solar industry, the United States responded in 2011 by imposing anti-dumping duties on Chinese solar panels up to 250% [BQE, 2013a].

As far as it was concerned, Europe reacted much later. Indeed, it has launched an anti-dumping investigation from September 2012, following a complaint from the European Association PROSUN. Thus, it has imposed since June 6, 2013 interim taxes on Chinese solar panels, but with a rate of only 11.8%, the Commission having decided to reply in two stages, to encourage Beijing to negotiate. Failing amicable settlement, the average rate would have been 47.6% on August 6, with lower fees (37.2%) for referred Chinese companies which have cooperated in the investigation and higher rights (67.9%) for those which did not. Finally, a compromise was signed on August 2 with an application on August 6. This compromise provides for an annual export quota of Chinese solar panels to the EU of 7 GW, with a minimum price of 57 cents per watt. Beyond the quota, Chinese exports would be subject to taxes of 47.6%. In the same way, the companies which will sell their panels with a price lower than 57 cent per watt will be taxed. China, which exported in 2012 a quantity of 12 GW of solar panels to the European countries, had previously proposed to cap the volume of its exports to 10 GW and sell them at a minimum price of € 0.50 per watt, against € 0.37 then, an increase of 35%, but below the expectations of the Commission [BQE, 2013b].

In the context of a sharp slowdown in the European market, the 7 GW quota does not seem a strong constraint, and so does the value of c€57/W which is still considered by the European professionals as dumping [Les Echos, 2013].

At present, it is unclear whether these measures will be effective to protect the European industry against trade attacks from China, at least for what is left of it. We can especially deplore that they

have not been implemented earlier, in a context of a European market highly driven by strong national support measures (see Chapters 3). Thus, for nearly two years many solar companies had been experiencing significant losses, sometimes leading to bankruptcy. Examples include the German "Q-Cells" (bankruptcy in April 2012), the Japanese "Sharp" (net loss of 545.35 billion yen - 4.14 billion euros, in fiscal year 2012-2013), the American "Solyndra" (bankruptcy in September 2011) and the French "Photowatt" (bankruptcy in November 2011; "EDF Energies Nouvelles" took over the business in February 2012). One could oppose that overproduction and dumping broke apart on the giant of the Chinese photovoltaic industry "Suntech" in March 2013 (the former number one in sales, with an output of 2,400 MW in 2011 had more than € 2.2 billion of debts). For specialists, this bankruptcy should not be seen as a sign of weakening of China, since the world leader is Chinese (Yingli Green Energy). For Enerpresse "the strategy of Beijing of international competitors elimination remains a success" [Enerpresse, 2013].

In order to illustrate the consequences of this strategy of dumping, we can have a look at the global market share of solar PV module manufacturers in 2012 (Figure 11). The top fifteen account for 50.2% of the global market. There are 9 Chinese companies, accounting for 35.2% of the global market.

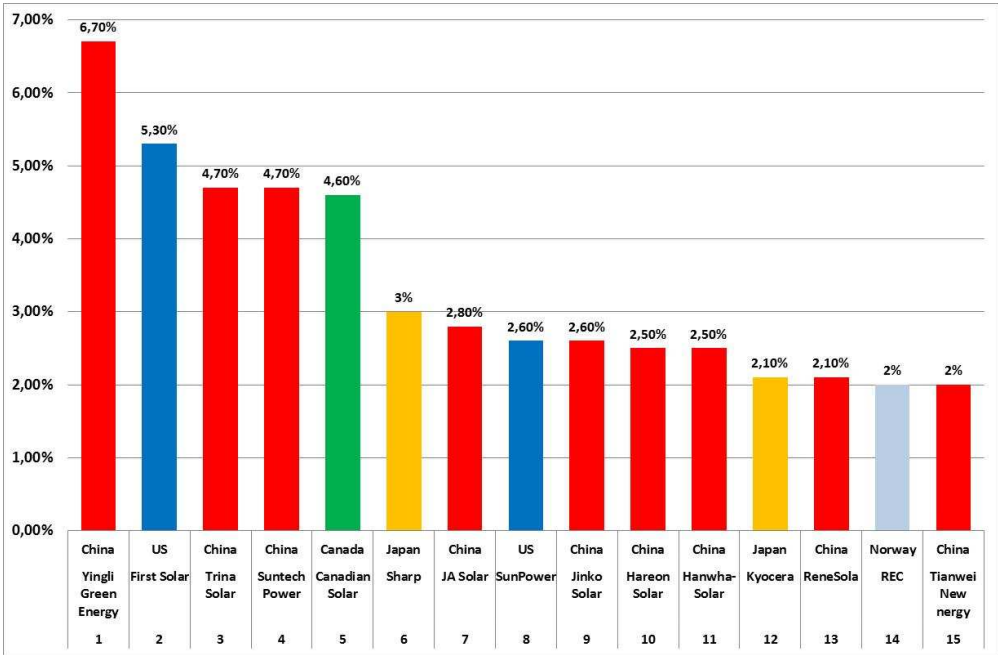


Figure 11: Global market share of solar PV module manufacturers in 2012 (Top 15) [Statista, 2013]

The dynamic of the global market share is also very meaningful. Indeed, when looking at Figure 12, we can observe the decline of the German PV industries in favor of Chinese ones from 2005 to 2011.

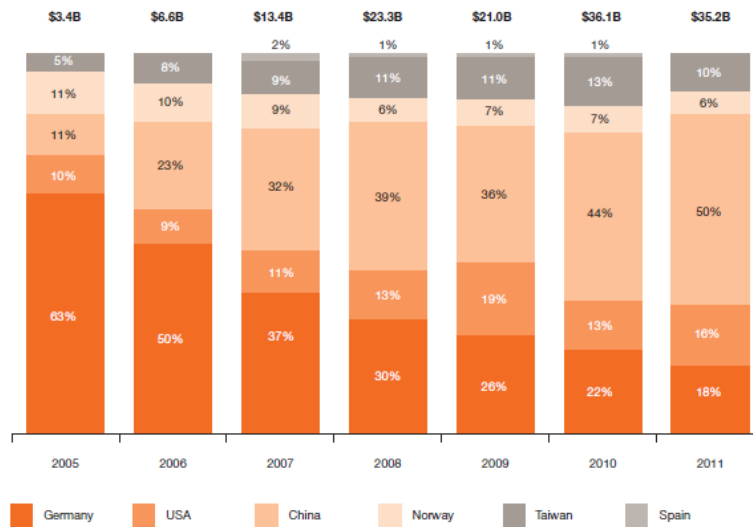


Figure 12: Revenue share by country from 2005 to 2011 [PWC, 2012]

Concerning the PV market, another point interesting to explore is the repartition of the different kinds of technologies. Today, the global PV market is dominated by crystalline silicon technologies (mono and multi crystalline). These devices account for nearly 85%-90% of PV production [Bagnal & Boreland, 2008, *in* Grau & *al.*, 2012]. According to the EPIA [EPIA, 2013], for the next five years it is expected to maintain its market share at levels of around 80%, considering both the maturity of the technologies (technical and economic maturity) and the high capacity of production, particularly in China.

Concerning the whole production line (polysilicon, wafers, c-Si cells, c-Si modules and thin film modules) some disparities also exist (Figure 13). Thus, Americas are the top region for polysilicon production (34% of the 2012 production), behind China (27% of the 2012 production), Europe (20% of the 2012 production) and Asia Pacific countries (19% of the 2012 production) [EPIA, 2013]. China dominates the wafers production with 80% of the global 2012 production. China and the Asia Pacific countries dominate the c-Si cells production with respectively 66% and 27% of the 2012 production. Finally, the modules market is dominated by China for the c-Si modules (69% of the global production in 2012) and it is dominated by the Asia-Pacific countries for thin film modules (62% of the global production in 2012).

Examining these figures, it is easier to understand why China has committed a response to the anti-dumping measure of the US and Europe on the PV modules by anti-dumping measures on the polysilicon, the only step on the whole chain that China is not dominating. Thus, the Chinese Ministry of Trade imposed since July 24, 2013 a tax on exports of polysilicon from the United States and South Korea. Customs duties are between 53.3% and 57% for U.S. producers and 2.4% to 48.7% for the South Koreans [Enerpresse, 2013b]. The same threats have weighed on Europe at the time of the

anti-dumping investigation on PV modules (as well as more specific threats by countries such as the wine in France or the Mercedes for Germany).

The PV market significantly grew these past ten years thanks to the European market, and will continue thanks to the Asia-Pacific region. This growth has an impact on the electric production (less use of fossil fuels but more intermittency) and consequently on the electricity market. It also has consequences on the industry sector since the PV market is very profitable and fast growing. Thus, problems of overcapacities and dumping were observed; they have been profitable for Chinese companies, rising up the issue of the national support to the PV market.



Figure 13: Global PV capacity versus production in 2012 by region (%)

5. Conclusion of the chapter one: PV is meant to have a strong place in the future energy mix

The aim of this first chapter was to establish the overall context and introduce our problematic, *i.e.* “what is and what could be the place of the solar photovoltaic energy in the global energy mix?”.

We first analyzed the issue of a sustainable mix and concluded that renewable energy should weigh more in the future. As we decided to focus our attention on PV, we then briefly presented the state of the art and potentials of the different PV technologies. There had been improvements both in terms of cost reduction and efficiency increase, but some avenues for reflection are still to be explored. Finally, we analyzed the PV market over the last ten years. This is a very dynamic market but this quick introduction had some bad consequences on the electricity market due to the fact that PV is not “dispatchable”. Furthermore, this fast growth also generates consequences on the public policy support in a context of a very aggressive market.

Considering the challenges developed in the general introduction, PV is meant to have a strong place in the future energy mix due to its high potential, the strong public support devoted to it (which accompanies its development) and with technologies that are still improving.

However, there is a technical challenge to wider its development: its intermittency, a solution to which being coupling PV to storage devices. This is the theme of the following chapter.

Chapter Two: Development of a multicriteria methodology for the evaluation of energy storage coupling as a solution to intermittency

1. Introduction of the chapter two

We have highlighted in the previous chapter the issues of the PV market in the coming years. According to the PV manufacturers, the main point is the cell prices that have to be as low as possible to allow a higher market penetration. From our point of view, in order to evaluate the economic viability of a PV project, it is necessary to consider the whole system in which the PV panels have to be implemented, meaning its localization (many differences in the solar irradiance for instance) and its technological environment (problem of the intermittency for instance).

PV-driven standalone systems, such as PV-battery configurations, suggest an off-the-shelf energy solution with a broad field of applications (telecommunications for instance) and a considerable research background [Chaurey & Deambi, 1992; Jossen & *al.*, 2004; Kaldellis & *al.*, 2009]. Other storages like hydrogen (H₂) have also been studied, but to a lesser extent [Richards & Conibeer, 2007; Carapellucci & Giordano, 2012].

When PV systems are connected to the electricity grid, there are alternatives to storage to solve the problems of intermittency. Thus, a gas power plant in back-up could be a cheaper solution, especially in the actual context of low gas prices (shale gas effect), but it generates CO₂ emissions; developing the electricity network in order to mutualize several production power plants also consists in a part of the solution, but it could not solve the problem by itself when there is a large amount of non-dispatchable energy connected to the grid (no sun at night); finally, a wider modularity in the electricity prices, *i.e.* demand-side management, could also act on the demand to better fit the production. Nevertheless, all of these alternatives present some tricky points, and even if it is still expensive, energy storage could also be a part of the solution portfolio to solve the problem of intermittency, even for connected PV systems.

So, to evaluate the economic relevance of a PV system, the aim of this chapter is first to present a methodology for multiobjective optimization of a whole chain of electricity production from PV panels (based on the total levelized cost and other criteria as detailed on the case studies in

subsection 3), and then to present a possible application of the developed methodology on an interesting case in *La Réunion* island.

This work was carried out in the context of a multidisciplinary project from 2007 until 2009 (see Appendix 1: The EDELVEISS project, page 126). The findings of this work, which correspond to this chapter, have been published through two articles in international journals with referees [Avril & al, 2010; Avril & al, 2011].

2. Methodology for the techno-economic optimization of a system coupling energy storage to PV

In order to optimize a system coupling energy storage to PV, we propose to proceed in several steps:

i/ We must choose the right devices both in terms of technological and economic potentials, regarding the selected place to install it. The whole system is so characterized by different parameters and behavioral equations related to each technology and to environmental data (meteorological data and electrical consumption). This is the techno-economic model of the system.

ii/ For a given configuration, we are able to calculate some variables, such as the total levelized cost of the whole system output or the occupied area for instance. We can also take into account constraints which can be intrinsic or extrinsic.

ii/ The final step is to implement the optimization process through a code which operates the simulation for a given configuration of the system and also performs multicriteria optimization under constraints. This lead us to the creation of the MOMuS code (*Modélisation et Optimisation MULTicritère du Stockage d'énergie* - Multicriteria modeling and optimization of energy storage), in strong relationship with our colleagues of the LGLS (*Laboratoire de Génie Logiciel et Simulation* – Laboratory of software engineering and simulation). The optimizations can be performed on the variables (calculated in phase ii) as well as on the parameters (defined in phase i) of the system, depending of what has to be tested (see the case studies in section 3), respecting the constraints (defined in phase ii).

These different steps are detailed in the subsections below.

2.1. General description of the system coupling energy storage to PV

2.1.1. Design of a connected PV system

As explained in the previous section, in order to evaluate the economic viability of a PV project, it is necessary to consider the whole system in which the PV panels have to be implemented, meaning its localization and its technological environment. Considering a specific place, our goal is to satisfy the electricity demand of consumers (the load) by producing electricity thanks to PV panels only. Of course, PV electricity output depends on the meteorological data of the site land and the characteristics of the chosen PV panels. The most often used PV panels are silicon crystalline (c-Si) PV panels, but depending on the available area, it is possible to use panels with a higher (respectively lower) efficiency but a higher (respectively lower) price.

Keeping in mind that we do not want to produce any CO₂ emission, gas back-up is not a preferred option. Thus, the load cannot be fully satisfied without storage technologies that must be chosen carefully considering the whole system. As we decide to test our method in an isolated place of a hundred inhabitants in the Island *La Réunion* (see the case studies in section 3), we choose to evaluate the relevancy of a battery-based storage system coupled with a hydrogen (H₂) chain made of an alkaline electrolyzer, a H₂ compressor, gaseous hydrogen (GH₂) storage in bottles and a proton exchange membrane fuel cell (PEMFC). Two kinds of batteries are simulated: lead-acid (Pb-A) and nickel-cadmium (Ni-Cd) batteries. For H₂ storage, only gaseous storage at 200 bar is considered. The choice of GH₂ solution results from the immaturity of the solid H₂ storage when the study was led and the too high energy cost of the liquid H₂ storage due to the liquefaction phase. The value of the pressure answers two criteria. On the one hand, a high pressure would increase the price too much since it requires expensive compressor and composite vessels. On the other hand, a sufficient pressure should be used in order to minimize the system size. Yet, a low pressure could be an interesting pursue if the output pressure of the electrolyzer is high enough to avoid the use of a compressor.

We also consider a weak connection to the grid, S_{max} , which represents the degree of intermittency of our system that is “acceptable” from the point of view of the transmission or distribution system operator.

The Photovoltaic-Battery-Hydrogen system is represented on Figure 14.

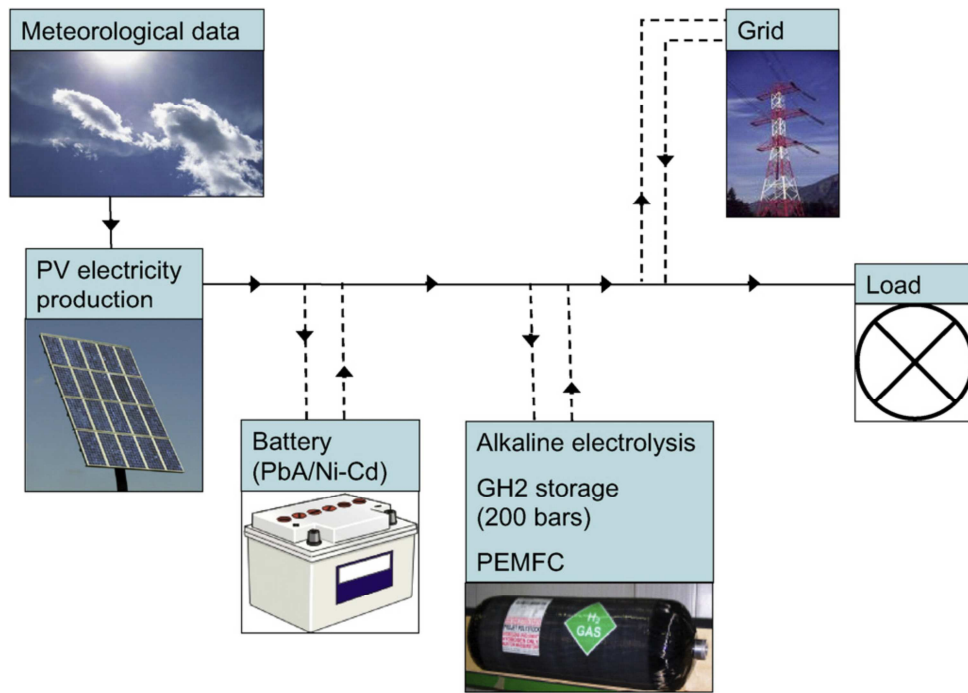


Figure 14: The Photovoltaic-Battery-Hydrogen system with a weak connection to the grid

To sum up, the site must be chosen and defined (meteorological data and consumption); then the technological devices must be selected relevantly; finally, the degree of intermittency of the system can be adopted.

2.1.2. Energy management of the system

The energy management of the system is a crucial element of the simulation. Indeed, it defines the priority between the components, which are both consumer and supplier of electricity, the ones for the others. To illustrate this, we can mention that the batteries consume electricity from solar panels and supply it to the load.

Although it is more expensive, in order to give the priority to the local production, we chose to give the priority to the electricity produced by the PV panels rather than the electricity bought to the grid. Besides, we do not allow a storage system to be recharged thanks to another one, considering the very bad efficiency it implies.

As a result, in our simulations, we have considered the following management rules:

Rule 1: The consumer has the priority for consuming electricity. It takes it prior from PV which is the local electricity production, then from the grid which provides the lowest cost, then from the batteries and finally from the H₂ system which delivers the most expensive electricity;

Rule 2: The batteries get recharged thanks to the PV electricity and then from the grid; an empty battery has the priority on another battery; thus limiting a too long discharge which could damage the storage system;

Rule 3: The H₂ system and the grid can take their electricity only from the PV panels, with a priority for the H₂ system.

2.2. Technical and economic design of the components

According to what is explained in the previous paragraph, we need to describe the technical and economic data for the PV panels, as well as for the two storage devices, i.e. the batteries and the hydrogen chain. This is done considering the different data for the two horizon times considered, the short term “2012” and the medium term “2020” (the study was led from 2007 to 2009).

2.2.1. Techno-economic model of PV panels

The electrical production of a PV panel P_{PV} can be calculated knowing the temperature of the cell T_c , the temperature of the cell in standard conditions T_{Cref} , the solar irradiance ξ , the solar irradiance in standard conditions ξ_{ref} , the standard peak power of a module P_{max}^0 , and the temperature coefficient μ_{Pmax} :

$$P_{PV} = \frac{\xi}{\xi_{ref}} \times P_{max}^0 [1 + \mu_{Pmax}(T_c - T_{Cref})] \quad (1)$$

The temperature of the cell T_c can be calculated from the outside temperature T_{ext} , knowing the nominal operating cell temperature (NOCT):

$$T_c - T_{ext} = (NOCT - 20) \times \frac{\xi}{800} \quad (2)$$

The panel chosen for the simulations is a Photowatt-PW6-123 Wp² [Photowatt, 2013]. Its characteristics are listed in Table 1. Considering the 2008 prices [Wiser, 2008], assuming an annual growth of installed MWp of 28% between 2011 and 2020, and a learning factor of 22% (see Appendix 2: The learning curve) as it is foreseen in the advanced scenario of the European Photovoltaic Industry Association [EPIA, 2008], the cell price would decrease from €3/Wp in 2012 to €1.48/Wp in 2020.

² Watt-peak (Wp) is a measure of the nominal power of a photovoltaic solar energy device under laboratory illumination conditions.

Table 1: Techno-economic characteristics of the 100 W photovoltaic panel and the inverter

P_{max}^0	100W
μ_{Pmax}	-0.43%/°C
NOCT	45°C
Investment of the cells in 2012	€3/W _p
Investment of the cells in 2020	€1.48/W _p
Investment of inverters, connectors, and installation (2012 and 2020)	€4/W _p
Maintenance	2% of investment
Life time of cells	25 years
Life time of inverters and connectors	10 years
Area occupied by one PV panel	4m ²
Area occupied by one inverter	0.13 m ²

2.2.2. The battery storage techno-economic model

We used the Shepherd model [Shepherd, 1965] for our simulation. It predicts the charge-discharge phenomena for both Pb-A and Ni-Cd batteries. It has been defined in strong links with the experts of the CEA. This model presents the relation between voltage u , current i and the battery state of charge q_{bat} as follows:

in discharge ($i < 0$):

$$u(t) = U_{CO,d} - G_d \times dod(t) - R_{int,d}(t) \times i_{bat}(t) \quad (3)$$

in charge ($i > 0$):

$$u(t) = U_{CO,c} - G_c \times dod(t) - R_{int,c}(t) \times i_{bat}(t) \quad (4)$$

where U_{co} is the battery output voltage, G the coefficient which characterizes $\Delta u = f(q_{bat})$, R_{int} the internal resistance, dod the depth of discharge and c, d are the subscripts of charge and discharge, respectively.

In a first approximation, we consider that the internal resistance is constant. So we have to evaluate continuously the depth of discharge dod which is the complementary part of the state of charge soc .

$$dod = 1 - soc \quad (5)$$

Neglecting the influence of the temperature, we obtain:

$$soc = \frac{q_{bat}}{C_{bat,N}} \text{ with } 0 < soc < 1 \quad (6)$$

in which $C_{bat,N}$ (A.h) is the nominal capacity and q_{bat} (A.h) is the capacity of the battery at the t time.

In the MOMuS model, we have firstly considered that $C_{bat,N}$ is constant. In reality, the nominal capacity in the discharge mode depends on the current intensity. Due to the time step considered in the below calculations (some dozens of minutes), we do not consider the effect of the temperature that has to be considered for smaller time steps (in the order of the minute). So, the relation used in our model is the one below:

$$C_{bat,N} = C_{bat,N,ref} \left(\frac{I_{ref}}{I} \right)^{N-1} \quad (7)$$

With:

$C_{bat,N,ref}$: Standard nominal capacity (A.h)
 I_{ref} : Standard nominal current (A)
 N : the Peukert's constant

The capacity of the battery q_{bat} is given by:

$$q_{bat}(t + dt) = q_{bat}(t) + q_{exc}(dt) + q_{self}(dt) \quad (8)$$

In this equation:

i) $q_{exc}(dt)$ represents the quantity of energy given or extracted from the battery; it is related to the current as follows:

$$q_{exc}(dt) = \chi \times i(t) \times dt \quad (9)$$

Here χ represents the efficiency of the charge of the battery; it varies with the conditions of operating (charge/discharge/overcharge):

$$\begin{aligned} \chi &= 1, \text{ if } i < 0 \text{ (discharge)} \\ \chi &= A_\omega, \text{ if } 0 < i < ig \text{ (charge)} \\ \chi &= A_\omega \times \frac{ig}{i}, \text{ else } (i \geq ig \text{ (overcharge)}) \end{aligned} \quad (10)$$

in which ig is the gassing current, depending on $C_{bat,N}$ and soc :

$$ig = \begin{cases} B_\omega \times C_{bat,N} \times (1 - soc) & \text{if } soc < soc_{max} \\ B_\omega \times C_{bat,N} \times (1 - SOC_{max}) & \text{else} \end{cases} \quad (11)$$

A_ω being an adimensional parameter for the charge efficiency and B_ω being in [h]

ii) $q_{self}(dt)$ represents the quantity of energy lost by the self-discharge of the battery. It depends on the value of the capacity of the battery:

$$q_{self}(dt) = - \frac{Q_s \times q_{bat}}{100 T_s} \times dt \quad (12)$$

Q_s is the self-discharge of the battery and T_s is the number of hours per day ($T_s = 24$ h)

To be valid, this model must respect the following operating areas:

$$VsocD \leq soc < 1; \quad (13)$$

this represents the fact that there is a minimum state of charge VsocD

$$u \text{ charge} < UC \text{ max}; \quad (14)$$

this represents the fact that there is a need to avoid electrical surge

$$u \text{ discharge} > UD \text{ max}; \quad (15)$$

this represents the fact that there is a minimum voltage UD max

$$i \text{ charge} < IC \text{ max}; \quad (16)$$

this represents the fact that there is a need to avoid overcurrent

$$i \text{ discharge} > ID \text{ max}. \quad (17)$$

this represents the fact that there is a minimum current ID max

The internal state of the battery is used to manage the pluggings and the unpluggings. It can be at three different states, depending of soc :

i/ Full: the battery becomes full as soon as $soc > socDfull$ and is no more full as soon as $soc < socCfull$,

ii/ Empty: the battery becomes empty as soon as $soc < socDempty$ and is no more empty as soon as $soc > socCempty$,

iii/ Standard: in other cases, the battery is plugged to the system in charge and in discharge.

Technical data for Pb-A and Ni-Cd batteries are given in Table 2.

The economic data mostly depend on the technologies. For this study, we have considered a Pb-A battery of 100 A.h with a tubular configuration and a Ni-Cd battery of 62 A.h. The first one currently costs €100 with about 500 cycles of life time, whereas the second one is more expensive, about €330 but with a longer life time, about 1000. We chose a Pb-A battery since it is nowadays the cheapest technology and a Ni-Cd battery which is on the one hand more expensive but on the other hand has a bigger depth of discharge and a higher number of cycles. At first, we have considered standard sizes to compare these two technologies, but it could also be interesting to study other sizing and other technologies such as lithium-ion batteries.

Table 2: Techno-economic data for Pb-A and Ni-Cd batteries

	Lead-acid battery	Nickel-Cadmium battery
R_{int}	0.1	0.005
$U_{co,c}$	14.3	17
$U_{co,d}$	13.5	14
G_c	1.14	1.5
G_d	1.08	5
$C_{bat,N}$	100	62
A_ω	0.98	0.98
B_ω	0.201	0.201
SOC_{max}	0.95	1
Q_s	0.16	1
n	1.2	1.2
UC_{max}	14.5	17
UD_{max}	12.6	9
IC_{max}	C/5	C/5
ID_{max}	C/2	C/2
$socDfull$	1	1
$socCfull$	0.96	1
$socDempty$	0.4	0
$socCempty$	0.45	0
I_N	10	6.2
Area occupied by one battery [m ²]	0.07	0.07
Cost of one battery [€]	100	330
Lifetime [number of cycles]	500	1000

2.2.3. The hydrogen chain storage techno-economic model

The H₂ chain is composed of four elements:

- i. During the charging time, the alkaline electrolyzers producing H₂ from electricity;

- ii. A compressor compressing H₂ from 30 bar to 200 bar;
- iii. A storage system comprising several 50 L cylinders and auxiliary components with a maximum allowable working pressure of 200 bar;
- iv. And PEMFC systems delivering electricity from the stored H₂.

Table 3 presents the characteristics considered for a 200 kW electrolyzer for the short and medium terms. This size has been selected in order to fit the electrical load data and to consider H₂ storage rather like long term storage in comparison to battery storage. Another solution would have been to consider smaller electrolyzers, which are more expensive. For medium term performance, it is assumed that the investment will be divided by five and that the electricity consumption will improve from 4.4 kWh/Nm³ in 2012 to 4 kWh/Nm³ in 2020. The optimistic assumption on the investment is in line with the goals of the Department of Energy (DoE) of \$300/kW, which leads to an investment of \$60,000 for a 200 kW electrolyzer.

Table 3: Characteristics of a 200 kW alkaline electrolyzer in 2012 and in 2020

Year	2012	2020
Minimal operating electrical power [kW]	50	50
Electricity consumption [kWh/Nm³]	4.400	4.024
Life time [year]	20	20
Investment [k€]	454	84.3
Maintenance [% of Investment/year]	6.4%	5%
Area occupied by one electrolyzer [m²]	10	10

Table 4 presents the characteristics taken into account for a 200 kW compressor. The power of the compressor is set in line with the one of the electrolyzer. This is a quite rough assumption, which has only a slight influence on the total levelized cost (the part of the compressor cost in the total levelized cost only represents a few percent). This is a mature technology and we do not foresee any performance or cost improvement for the medium term.

Table 4: Characteristics of a 200 kW compressor

H2 output [Nm³/h]	46
Lifetime [h]	40,000
Electricity consumption [kWh/Nm³]	0.27
Investment [€]	68,927
Maintenance [% of Investment/year]	10%
Area occupied by one compressor [m²]	3.5

Concerning the H₂ storage system, it is assumed that “B500 bottles” that correspond to 50 L cylinders and their corresponding auxiliary components reach a total conservative cost of €1000 per cylinder. A life time of 10 years is also considered.

Finally, Table 5 presents the technical and economic data taken into account for PEMFC systems. A power of 25 kW has been considered, since it is in range with what is proposed by the manufacturers (typically from 1 kW to 50 kW). For the medium term, no technical improvement is considered; the only change concerns the important cost reductions which are expected to result from an assumed large scale manufacturing of these PEMFC systems (500,000 units).

Table 5: Characteristics of a PEMFC system

Maximum power of the PEMFC stack [kW]		25
Power needed for the auxiliaries [kW]		5
Investment [€]	2012	75,000
	2020	2,500
Maintenance [€/year]	2012	7,500
	2020	250
Life time [h]		2000
Area occupied by one PEMFC [m²]		1.7

2.2.4. The techno-economic model of the connection to the grid

Coupling energy storage is particularly interesting when considering peculiar situations such as remote and insular areas. In this regard, the interest of our approach will become visible through the applications presented in section 3 dealing with the example of the village of *La Nouvelle* located in the “*Cirque de Mafate*” in the *Réunion* Island. As for many insulated situations, the grid of *La Réunion* is more sensitive to electric load variations. That is why, it would be necessary to analyze the consequences of adding a supplementary line. Focusing on the *La Nouvelle* village case, it is not connected to the electricity network and will certainly not be connected shortly because of the expensive cost of deriving a transmission line in this hilly place. Notwithstanding this particular situation, we investigate the possibility of connecting this site to the grid. The idea is to evaluate if such a connection could have a real value. When compared to the capacity of the total electric network of *La Réunion* Island, the electric consumption of a village like *La Nouvelle* remains very small. As a result, from the village’s point of view, the grid is an infinite source or sinks for energy, only limited by the transmission link. In our model, we will assume that this transmission line already exists and thus we neglect the related connecting cost. Furthermore, to limit possible perturbations on the grid, this connection is assumed to be small.

The concept of a weakly connected site implies the existence of a grid which can exchange a limited quantity of electricity. Electricity could then be sold to the grid when there is an overproduction by the PV panels relating to the load profile, or could be bought when there is a lack of production to supply the consumer demand. During week days, the electricity can be bought at €0.094/kWh between 7 and 10 a.m. and between 6 and 9 p.m. During the other periods, it can be bought at €0.038/kWh. Concerning the sale to the grid, we chose the tariff of Electricité de France (EDF) used for building-integrated PV for Corsica and the French overseas departments which was €0.60176/kWh in 2009.

Table 6: The considered prices of electricity

Electricity from the grid (peak hours)	€0.094/kWh
Electricity from the grid (off-peak hours)	€0.038/kWh
PV feed-in tariff	€0.60176/kWh

2.3. The outputs of the model

Our MOMuS code performs simulations on 20 years. According to the different parameters, including the number of each technological device, several variables can be calculated for a given configuration:

- The total levelized cost,
- The customer satisfaction,
- The total occupied area.

2.3.1. The total levelized cost

In order to evaluate the system cost-efficiency, we have to calculate the total levelized cost of the electricity production TC (Eq. 18). The numerator has two main groups of factors, the first being the investment cost and the second the operating cost. The denominator is the electricity production per year (kWh/year). TC is expressed with the following formula:

$$TC = \frac{\sum_{t=1}^{T_i+T_e} [(C_i)_t + (C_o)_t](1+\tau)^{-t}]}{\sum_{t=1}^{T_i+T_e} [(P_t)(1+\tau)^{-t}]}$$

$$TC = \frac{\sum_{t=1}^{T_i+T_e} e [((C_i)_t + (C_o)_t)(1+\tau)^{-t}]}{\sum_{t=1}^{T_i+T_e} e [(P_t)(1+\tau)^{-t}]}$$
(18)

in which C_i is the cost of investment, C_o the cost of overheads and maintenance, P the produced energy, T_i the time of investment, T_e the time of operation, τ the discount rate and t the considered year. Note that we have not considered any cost of dismantling here. Such a contribution can be neglected for this type of systems, especially due to discounting effects.

In what follows, we have considered a discount rate of 8%, which is more pessimistic than the 5% chosen by [Gonçalves da Silva, 2010] (the higher discount rate, the higher levelized production cost) and a time of operation of the whole system of 20 years.

2.3.2. The degree of satisfaction of the customer

We also decided to take into account the concept of “customer satisfaction”. It represents the granted risks [Batut, 1987] and the social acceptability. This concept requires to be clarified. Indeed many issues such as the consumer habits, convictions, etc. may be involved in its definition. In this study, we restrict this concept to the energy supply rate (ratio between delivered electricity and requested electricity). Thus, considering a “customer satisfaction” of 100% means that no failure is acceptable, while accepting a lower “customer satisfaction” can lead to a lower cost and better suits the consumer needs.

2.3.3. The total area occupied

Knowing the surface area occupied by each technology unit $S[i]$ and the number of elements required $nb[i]$, it is easy to calculate the area occupied by the set of elements:

$$S = \sum_{i=1}^5 nb[i] * S[i] \quad (19)$$

With $i = 1$ correspond to the PV panels;

$i = 2$ correspond to the batteries;

$i = 3$ correspond to the electrolyzers;

$i = 4$ correspond to the compressors;

$i = 5$ correspond to the PEMFC.

The total area occupied by the system is an important factor, because it can be a constraint to the implementation of a project.

2.4. Optimization under constraints through the implementation of a home-made code: MOMuS

We presented the foundations of the model. In order to perform simulations and optimizations we developed the MOMuS code. Its architecture, the communication between the different modules and of course the multi-objective optimization method are presented hereafter.

2.4.1. Brief overview of the existing models

At the start of the project, our initial goal was to develop our own numerical tool. This was motivated by the fact that we wanted to model the technologies in strong relation with our R&D staff in order to use the most reliable and the most recent data. To carry out an efficient approach among existing codes analyzing the integration of renewable energies into various energy systems, we first analyzed the peculiar requirements of the EDELVEISS project (see Appendix 1). A good review of the different existing computer tools was carried out by Connolly & *al.* [Connolly & *al.*, 2010]. They have considered 68 tools and finally compared 37 ones, in collaboration with the tool developers or recommended points of contact. A first indication of the comparison was the number of users in terms of downloads or sales. Then, the comparison aimed at specifying different types of tools: simulation tools (simulating the operation of a given energy system to supply a given set of energy demand), scenario tools (medium and long term simulated prospects), equilibrium tools (including market economy), top-down tools (macroeconomic tools which determine growth in energy prices and demand), bottom-up tools (identifying and analyzing the specific energy technologies and thereby identifying investment options and alternatives), operation optimization tools (optimizing the operation of a given energy system), and finally investment optimization tools. None of the considered tools does all these tasks. Considering our developed MOMuS code, we can say that it is a simulation tool, a scenario tool, a bottom-up tool, an operation optimization tool and an investment optimization tool, but it is not an equilibrium tool. In this sense it offers more possibilities to the user than the most used codes, namely: RETScreen, HOMER, LEAP, BHP Screening Tool and energyPRO. Connolly & *al.* also classified these tools considering the different types of analyses that can be completed. Taking into account the geographical area, the timeframe scenario and the time step they were able to propose a classification opposing national energy system tools and tools with a specific focus. MOMuS clearly belongs to the second category, and more precisely to the time-step simulation tools. Finally, they compared the tools in regards with the energy sectors and renewable energy penetration. Other reviews propose other criteria for the classifications. Baños & *al.* [Baños & *al.*, 2011] thus considered the renewable energy technologies that the model can describe. Furthermore, Erdinc & Uzunoglu [Erdinc & Uzunoglu, 2012] are axing their paper on the optimization

techniques used for hybrid renewable energy system sizing, showing higher utilization of genetic algorithm, particle swarm optimization and simulated annealing. A combined approach considering the optimization method and the modeled technologies is led by Fadaee & Radzi [Fadaee & Radzi, 2012]. Finally, we can say that those models often consider simplified representation of the renewable technologies, as well as of the storage technologies. A recent tool developed by Guinot & *al.* [Guinot & *al.*, 2013a,b] focus on considering a more detailed description of the hydrogen chain components.

2.4.2. Architecture of the MOMuS code

The MOMuS code was especially developed in the context of the EDELVEISS project by the CEA laboratory LGLS. My role in the design of this code was to define the objectives of this code and provide the techno-economic model and optimization rules. The programming was achieved by colleagues of mine who are experts in numerical optimization methods. After exploring different possibilities, a Particle Swarm Optimization Algorithm was finally adopted. This is a method to perform numerical optimization without explicating the gradient of the variables to be optimized.

Briefly introducing this optimization method originally put forward by Kennedy and Eberhart in the mid-nineties [Eberhart & Kennedy, 1995; Kennedy & Eberhart, 1995], it originates from swarm intelligence. To illustrate its principle, we can invoke the research of bird and fish flock movement behavior. Indeed, while searching for food, birds are either scattered or fly together before locating the place where they can find food. Among the birds searching for food from one place to another, one can smell the food very well, being the bird that has the best food resource information. Since they are communicating and transmitting the information when searching around food, especially the relevant information, the birds will eventually flock to the place where food can be found.

Thus, solution swarm is compared to the bird swarm, the birds back and forth movements represent the development of the solution swarm, relevant information stands for the most “optimist” solution (i.e. the solution that minimizes the objective among all the considered ones, for a minimization problem), and the food resource corresponds to the most “optimist” solution during the whole process (i.e. the minimum that is searched for, for a minimization problem). The most optimist solution can be worked out in particle swarm optimization algorithm by the cooperation of each individual. The particle without quality and volume serves as each individual, and the simple behavioral pattern is regulated for each particle to show the complexity of the whole particle swarm. This algorithm can so be used to work out complex optimization problems.

In our problem, the MOMuS code is then architected as a set of several entities (see the Unified Modeling Language Diagram on Figure 15):

- i/ a scenario which defines the external conditions of the system for each time step of the simulation;
- ii/ the components of the energetic chain which provide and/or consume energy;
- iii/ the tactical management module of the energy distribution;
- iv/ the simulator which supervises the entire structure.

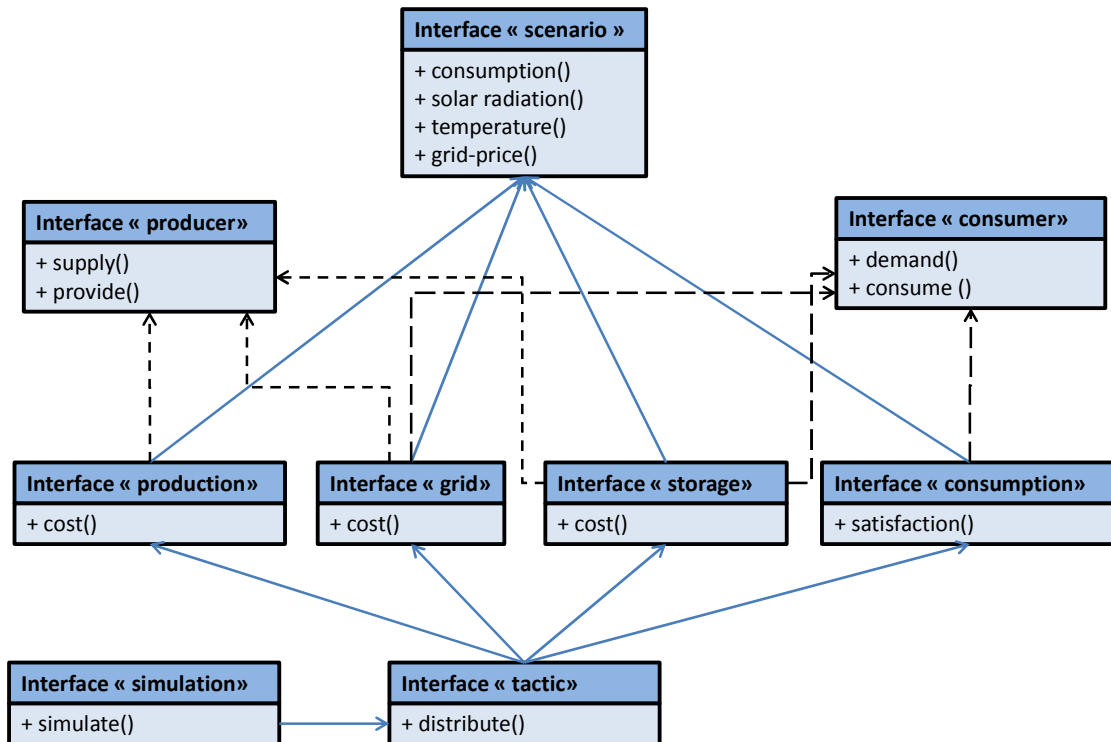


Figure 15: Unified Modeling Language Diagram of the MOMuS code

Let us now describe the simulation principle. At each time step, the simulator polls the tactical management to allocate the use of energy between the different organs of the chain. Each of the energy producing components, respectively energy consuming, are polled by the tactic block in order to determine the incoming, respectively possibly out coming, energy fluxes. Then according to the above mentioned rules, the energy repartition is performed and the time iteration is made until the end of the simulation. When the simulation process is over, we are able to recover the costs of each component and indications on other points: the consumers' satisfaction rate, the covered area by the panels, the batteries and hydrogen devices solicitation.

2.4.3. Communication between the different modules of the MOMuS code

The components of the energy chain are systems made of elementary sub-components which may supply, consume or store energy. Each of these sub-components is characterized by a cost and an operating rule. Then, to obtain the components, sub-components are assembled according to two standard approaches:

- the composition of several sub-components to obtain a complex operating component (for instance the hydrogen storage system is composed by the alkaline electrolyzers, the compressors, the storage cylinders and the fuel cells, cf. paragraph 3.3 of this chapter);
- the replication which treats a large number of identical sub-components (for instance the solar panels) thanks to a unique equivalent component.

Note that this replication approach cannot be used for some sub-components such as the fuel cells since they are not supposed to always work in concert.

At each time step, **the tactical management module** collects the energy supplies and demands of the components to regulate the balance between the energy that is consumed and/or produced by these objects. Finally, each component has to update its internal state before iterating.

To dispatch energy, the tactical management module has thus to evaluate the available and required energy of the different components. Note that the energy demand has to integrate the cost of the power units, the electric power range and possibly threshold values of some components (for instance, the lead batteries have to keep a minimal charge). Then, the control rules are managed through system prices. They consist in first supplying the most expensive consuming components with the energy provided by the cheapest producing ones. This first tactic ends when the supply or the demand is over, or when the supply cost is higher than the demand one. This second case typically prevents batteries to be reloaded thanks to their own energy. This main rule may be slightly modified for specific cases. For instance, if some produced power is still available at the end of the dispatching process but cannot be stored in some components due to a threshold reason, some other components will decrease their energy price to make it possible to use this remaining energy. Again, this energy retrocession is not acceptable for all the components (typically, the consumers satisfaction has the priority).

Furthermore, **the scenario module** defines the external conditions of the system in terms of consuming data or environmental data (solar radiation, temperature, etc.)

2.4.4. Multiobjective optimization method

Our goal is to optimize several objectives that are in conflict (usually two objectives are simultaneously considered, mainly for results processing reasons, see section 3 of this chapter), meaning that there is no way to fully satisfy both of them. So, solutions we are searching for are the compromise set, as it is defined by Pareto. When a solution belongs to this set, you cannot find another one that will best satisfy all the objectives: if it is better on one objective, it will be worse on another one. For instance, in the application case number one (see section 3), we will analyze the relevance of different storage devices that have to be as cheap as possible (the first objective is so to minimize the total levelized cost) and which reduce the degree of intermittency (the second objective is so to minimize the S_{max} parameter defining the limited electric power that we can exchange with the grid). Of course, solutions minimizing one single objective belong to this set. Other solutions are compromises between them.

Constraints can also be managed by the optimization process. In what follows, we consider two constraints: one for the consumer satisfaction, and one for a right usage of Pb-A battery. Satisfaction needs to be upper than 97% in terms of amount of requested energy per year (expressed in kWh/year). Pb-A batteries need to be frequently fully recharged otherwise they will suffer a loss of capacity due to the sulfation phenomena [Catherino & *al.*, 2004] (we assumed 20 days maximum between two recharged states) and cannot be used as long term storage. This constraint is not needed for the Ni-Cd batteries which do not have to be recharged so often. This is an additional advantage even if they are more expensive.

Thus we are dealing with a problem of multiobjective optimization under constraints. Note that this optimization process is performed simultaneously for all objectives. The MOMuS code includes the detailed techno-economic model and an optimization algorithm based on swarm particles. Moreover a parallelization of the code can be made to reduce the calculation time. For a given scenario (given site, horizon time, technologies of storage, management of the energy) the MOMuS code modifies the arrangement of the system by changing the number of PV panels, batteries, electrolyzers, H₂ bottles and PEMFC systems. The criteria are assessed for each system arrangement, or, in other words, possible solution. We finally obtain the whole solution set that simultaneously optimize the selected criteria, while satisfying the considered constraints.

3. Application of the methodology: conception of a power production system made up of PV and energy storage devices for an isolated area *Mafate*

The aim of the developed methodology is to assist researchers in defining R&D goals and in designing new renewable systems. In order to test our developed MOMuS code, we performed multiobjective optimizations under constraints considering two different scenarios on an isolated area *Mafate*:

- Case1: the relevance of different storage devices is analyzed considering both the total levelized cost and the degree of intermittency;
- Case2: the relevance of different PV cells is analyzed considering both the total levelized cost and the occupied area.

Optimal system designs can then be derived depending on the selected criteria. By considering different time horizons, R&D goals can be identified: what are the required performance improvements to achieve economic competitiveness?

3.1. General context of the island site of *Mafate*

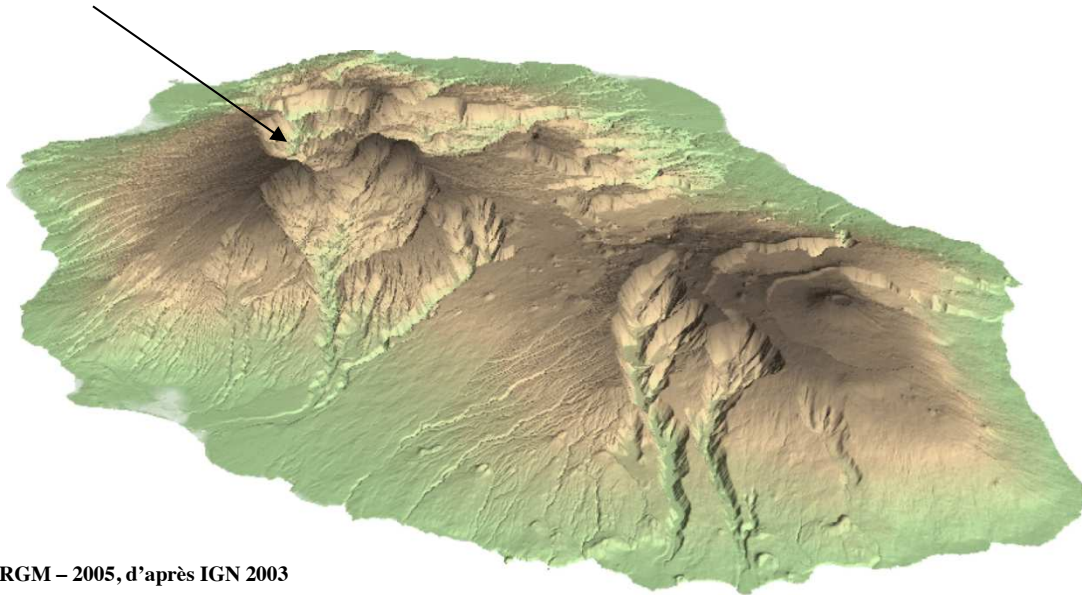
3.1.1. The isolated situation of the “*Cirque de Mafate*”

Satisfying the energy demand has now become a sensitive topic in the world, especially in insular areas, in addition to the need to limit fossil fuel consumption for both sustainability and energy self-sufficiency issues. Thus, the European Commission has set a goal of 22% of electricity production from renewable energies in 2010 for the whole electricity consumption in Europe [Directive, E. U., 2001]. Likewise, in the particular case of the French island *La Réunion*, an electrical self-sufficiency in 2025 is targeted [PRERURE, 2003]. Thus, we decided to test our model to optimize renewable electricity production coupled to storage technologies in the *La Nouvelle* village [Avril & al, 2010; Avril & al, 2011].

The site of *La Nouvelle* in the cirque of Mafate on the French island *La Réunion*, in the Indian Ocean, is only accessible on foot or by helicopter. The annual consumption of the 750 inhabitants is provided by the Regional Energy Agency in *La Réunion* (ARER) [Lacassin & Vinard, 2008], presenting a peak of electrical consumption of 140 kW. We assumed that it is weakly connected to the grid (at the present time, the electricity is produced by diesel generators). To reach the objective of energy independence by 2025, our goal is to satisfy the electricity demand of the consumers (the load) by

producing electricity thanks to PV panels only. Indeed, due to green energy pressure and the guiding rules predicted by the PRERURE, the fossil fuels are planned to be replaced. Of course, PV electricity production depends on the meteorological data of the site land. These fluctuating data are also provided by the ARER [Lacassin & Vinard, 2008]. The load cannot be fully satisfied without storage technologies and we have evaluated the relevancy of a storage system based on batteries coupled with a H₂ chain as described in Section 2.

The cirque of Mafate



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Figure 16: Localization of the cirque of Mafate on the Island *La Réunion*

3.1.2. The meteorological data of the “Cirque de Mafate”

The meteorological data have been given by the Regional Agency of Energy in La Réunion with an hourly precision [Lacassin & Vinard, 2008]. Analyzing them, it appears that producing electricity using wind power is economically unfeasible since the wind speed never surpasses the very low value of 10 m/s as shown in Figure 17. This validates *a posteriori* the choice of an electricity production based on PV panels which emit little GHG. Note that PV is dependent on both solar irradiance and ambient temperature.

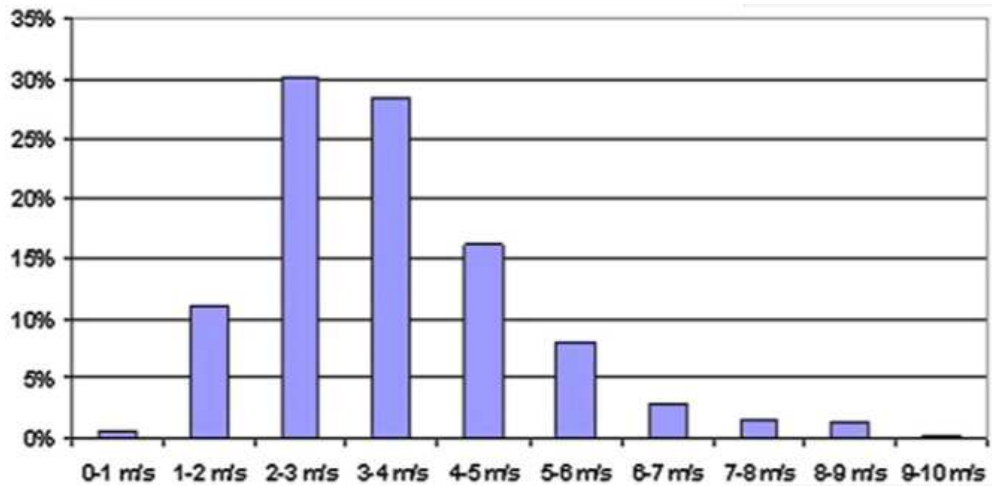


Figure 17: Annual distribution of wind speeds in *La Nouvelle*

3.1.3. Electrical data of the “Cirque de Mafate”

The annual electrical load profile used for the simulations was also given by the ARER [Lacassin & Vinard, 2008]. It has been elaborated from a behavioral study of the inhabitants of *La Nouvelle* with an hourly precision, taking into account daily, weekly and seasonal attitudes. For instance, the electric demand is higher in the evening than at noon and, due to the additional consumption of the tourists, is lower from Monday to Friday than in the week-end. Figure 18 presents the hourly profile for one week. Note that the maximum instantaneous electricity consumption in the year is about 140 kW. This annual profile is duplicated to cover the 20 years period of our study. This assumption is based on the fact that the demand of this isolated place, depending on limited tourism (no industry), is supposed to stay stable over the 20 years.

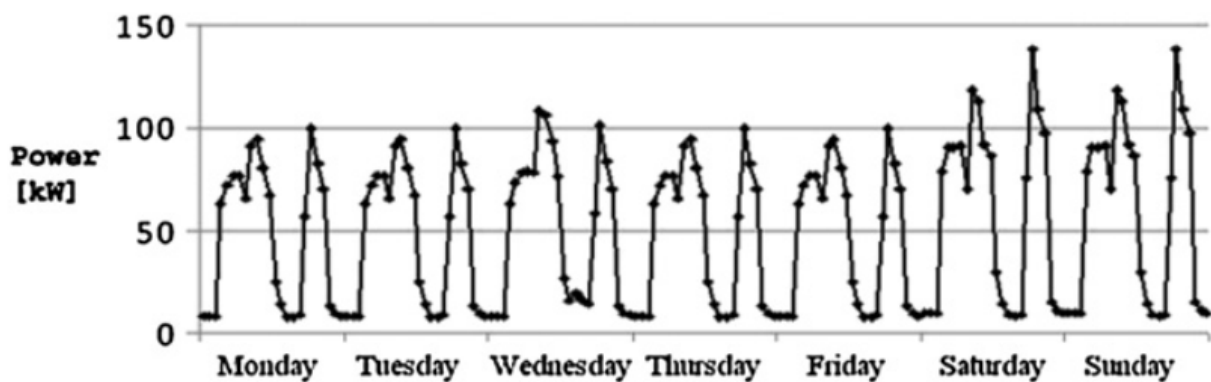


Figure 18: Load profile for a week in September

3.2. Case study n°1: Minimization of the total levelized cost and the connection to the grid

3.2.1. Case study n°1: Description of the study

Our goal is to test different storage devices in order to minimize both the total levelized cost TC of the whole system and its degree of intermittency which is represented thanks to the grid connection S_{max} (allowed in the 1-10 kW range), while granting at least a 97% consumer satisfaction rate

The computational results are presented at the short and medium terms (namely “2012” and “2020”) using the data presented above.

3.2.2. Case study n°1: Short term computational results

In this paragraph, different scenarios for the short term are presented.

First, in order to highlight the role of the storage, we have studied a case of a PV electricity production with no storage at all and no constraint on customer satisfaction. This scenario leads to an electricity production cost between €0.63 and €0.86/kWh which is in the range of the PV production cost when the simulations were performed [Ministry of Economics, Finance and Industry of France, 2008]; these costs decrease when increasing the connection to the grid since the price of electricity from the grid is lower than from the PV panels. In return, the satisfaction of the consumer is very low, of 60% for a small connection to the grid and lower than 70% for the maximum grid connection of 10 kW.

When adding storage composed of Pb-A batteries and a hydrogen chain, and imposing a minimum satisfaction of the consumer of 97%, we can observe an overcost between 10 and 30%, in the range of €0.20/kWh, compared to the previous case. This corresponds to the difference between “electricity when possible” and “electricity when wanted”.

We have also tested a storage composed of Ni-Cd batteries and H₂. The overcost is then higher than 100%, in the range of €0.9/kWh. It means that a storage which uses Ni-Cd batteries cannot challenge Pb-A batteries for this time frame despite their longer lifetime.

Figure 19 synthesizes these three cases: i) PV panels and no storage (blue triangles); ii) PV panels with a storage composed of Pb-A batteries and a hydrogen chain (orange diamonds); iii) PV panels with a storage composed of Ni-Cd batteries and a hydrogen chain (green squares). Each point of the figure corresponds to a specific size of the system, with a specific number of PV panels, batteries, electrolyzers, B50 bottles and PEMFC, *i.e.* a system arrangement design that corresponds to a compromise between the two selected objectives.

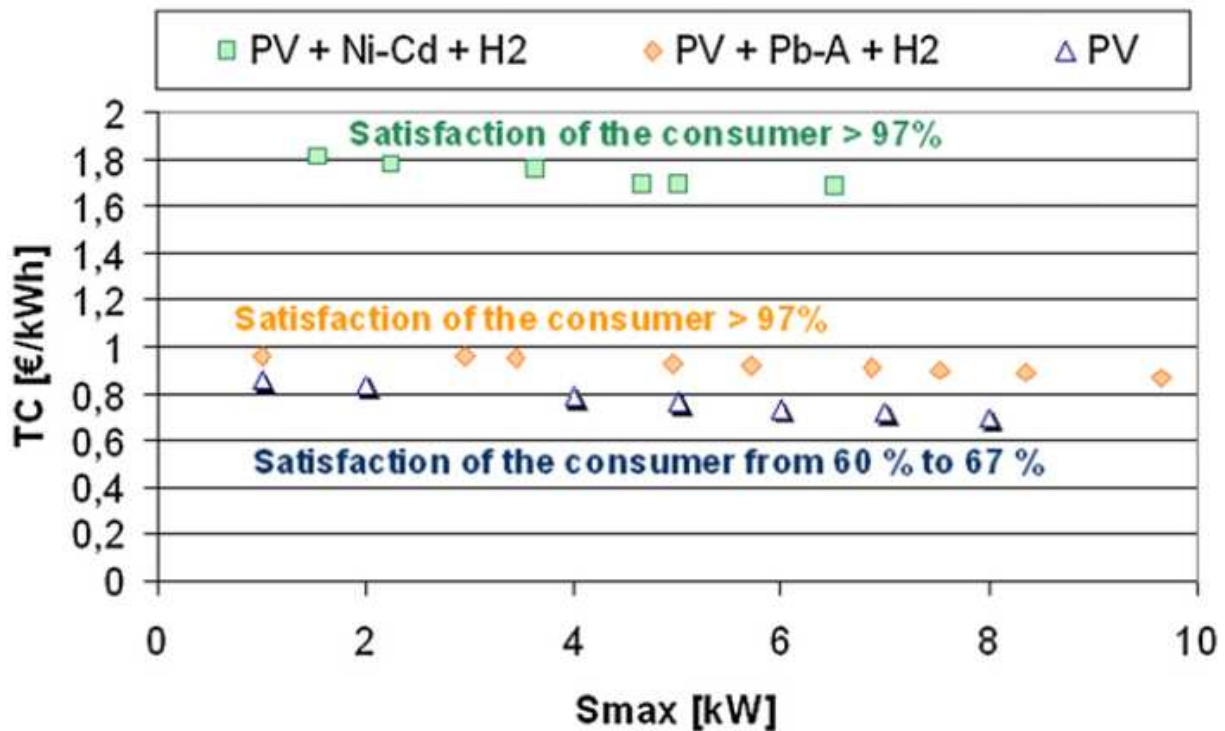


Figure 19: Total levelized cost for the short term versus the connection to the grid for three cases: i) PV without storage ii) PV & Pb-A batteries & H₂ chain iii) PV & Ni-Cd batteries & H₂ chain

3.2.3. Case study n°1: Medium term computational results

Dealing with medium term results, Figure 20 represents the same three cases as those studied for short term. The same legend as in Figure 19 is used.

There is a sharp decrease in the costs of PV panels and of the H₂ chain storage system compared to the short term data. So, the case with no storage at all leads to an electricity cost between €0.20 and €0.35/kWh depending on the connection to the grid; on the other hand the range of the rate of consumer satisfaction is the same as in the short term, *i.e.* lower than 70%.

When adding storage composed of Pb-A batteries and a hydrogen chain while imposing a minimum satisfaction of the consumer of 97%, we can notice an overcost of €0.20/kWh. It is the same as for the short term but it represents a higher percentage (60-100%) because of the cost reduction of the PV panels and no improvement for the Pb-A batteries (mature technology).

The storage composed of Ni-Cd batteries and a hydrogen chain leads to an overcost of €0.26/kWh. This is only 10% higher than the storage of Pb-A batteries and H₂. For this time frame, the cost gap is not wide enough to be the only criterion on which basing the decision between these two storage options. We can also take into account the surface occupied which is strongly related to the number

of each element, and specifically to the number of PV panels, or environmental criteria which could lead not to use batteries due to the risk of local pollution.

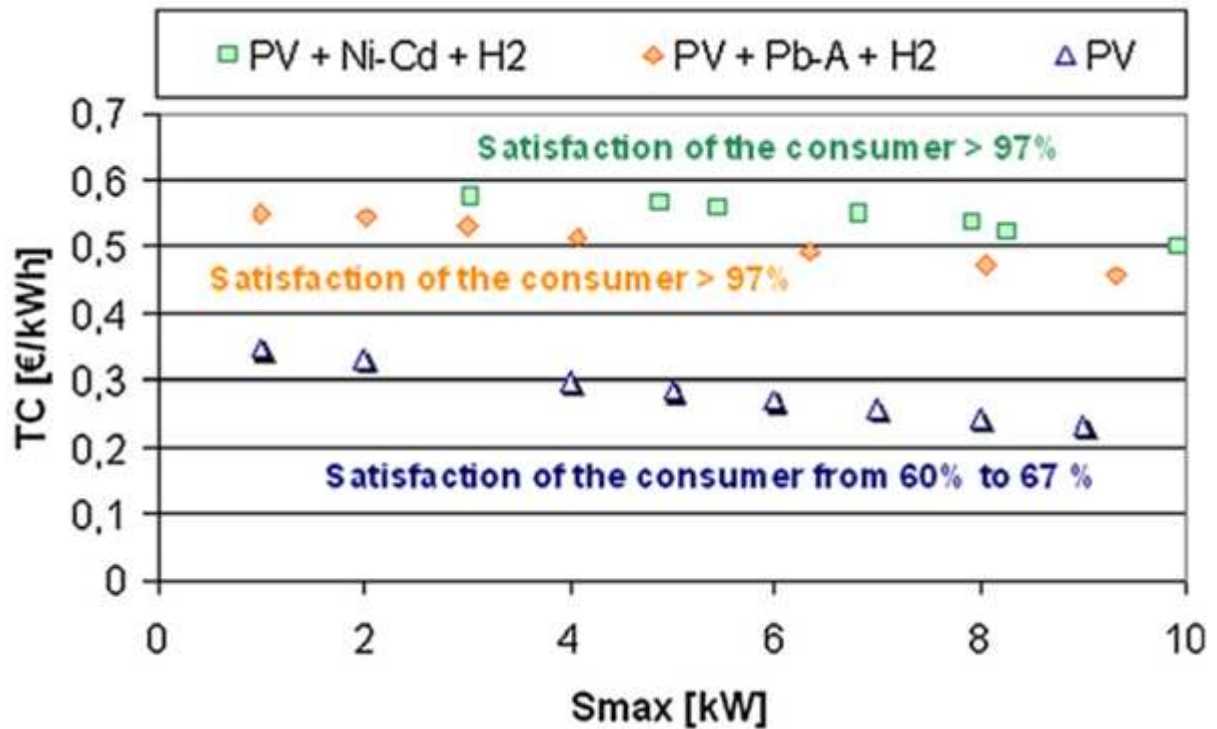


Figure 20: Total levelized cost for the medium term versus the connection to the grid for three cases: i) PV without storage ii) PV & Pb-A batteries & H₂ chain iii) PV & Ni-Cd batteries & H₂ chain

3.2.4. Case study n°1: Competitiveness between batteries and hydrogen system

In order to compare the different storage technologies, we have checked the number of each technology device (PV, batteries, electrolyzers, H₂ bottles and PEMFC systems) required for each optimal point of the two scenarios for short and medium term and we have calculated the quantity of energy that can be stored in the Pb-A and Ni-Cd batteries, and in the B50 bottles for hydrogen. Figure 21 represents the energy that can be stored in the batteries (in pink) and in the H₂ bottles (in light blue), whereas Figure 22 represents the installed PV capacity in MWp. The range of values is due to the different optimal configurations of S_{max}.

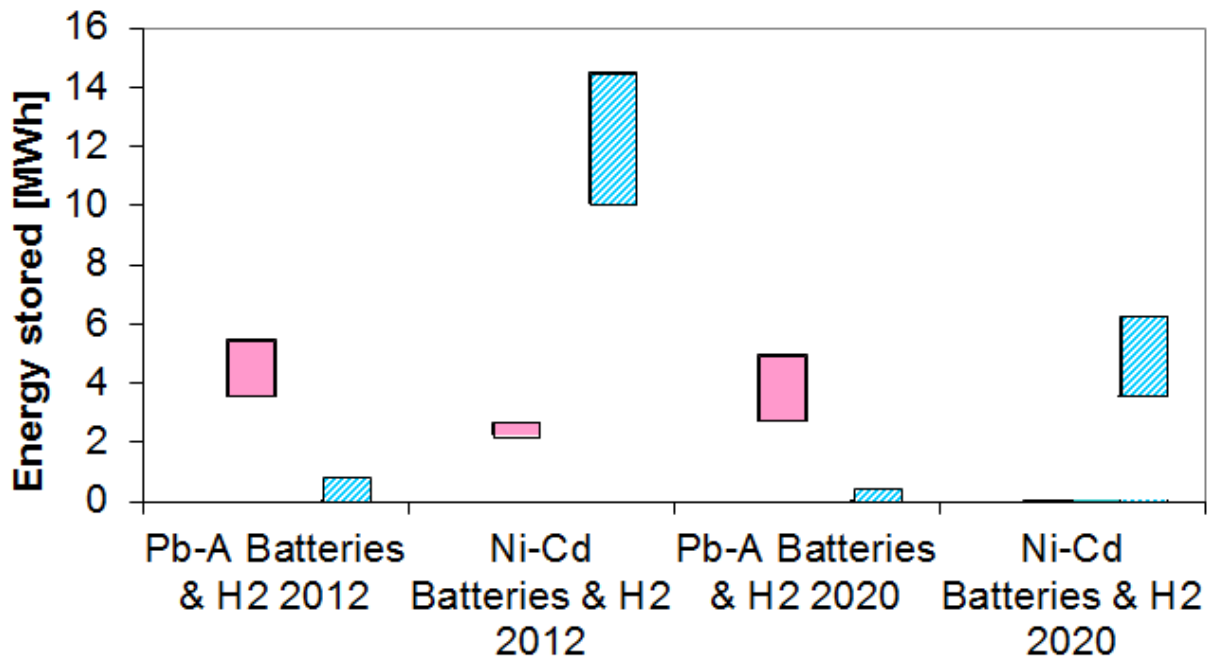


Figure 21: Energy in MWh which can be stored in the Pb-A and Ni-Cd batteries (in pink) and hydrogen bottles (in blue) depending on S_{max} for short and medium term.

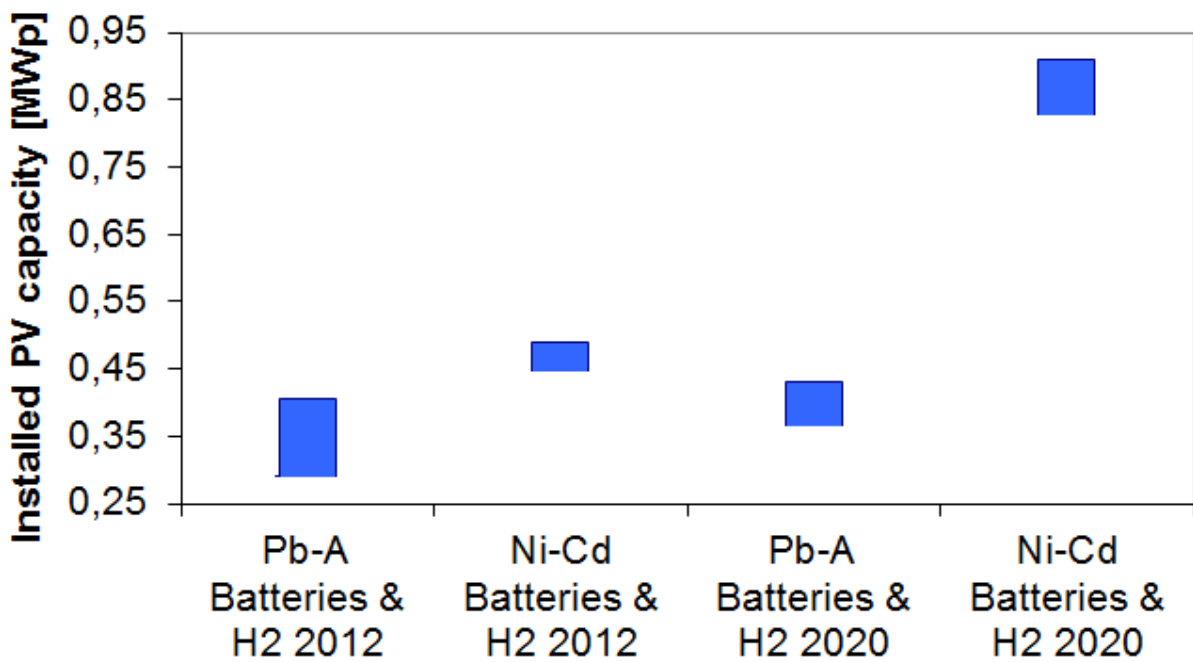


Figure 22: Installed PV capacity in MWp depending on S_{max} for short and medium term

Concerning the scenario with Pb-A batteries and H₂ storage, it appears that the storage is principally performed through the batteries for the two time horizons. The energy stored in the batteries represents 81% to 99% of the total stored energy for the short term, and 87% to 99% for the medium term. The hydrogen chain is considered as a seasonal storage as visible in Figure 23. Thus it

discharges during the winter (when the needs of electricity are higher) and charges during the summer. The main difference between short and medium term consists in the higher number of PV panels for horizon time “2020” which reduces the number of needed storage technologies. The system appeals more to PV thanks to its increased performances.

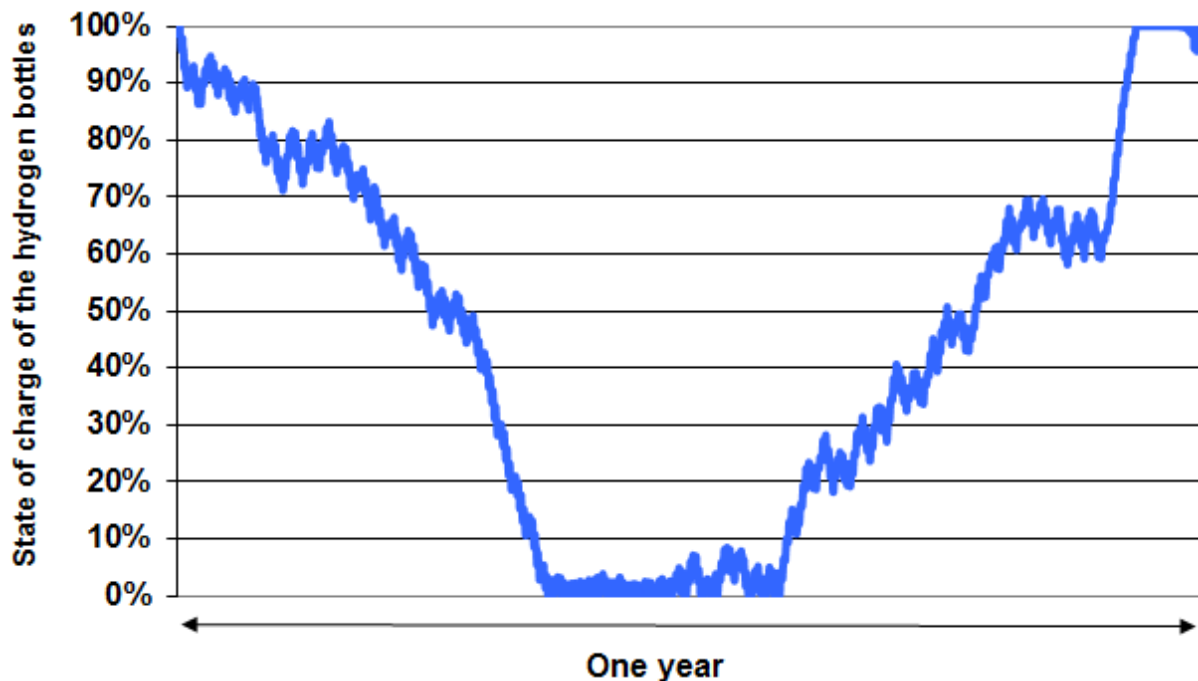


Figure 23: State of charge of the hydrogen bottles during 1 year for the short term – Pb-A coupling

For the scenario with Ni-Cd batteries and H₂ storage, the situation is quite different. For the short term, these two kinds of storage technologies are used, with a strong preference for the H₂ technology which represents between 79% and 87% of the capacity of energy storage. For the medium term, the number of Ni-Cd batteries is insignificant (between 0% and 2% of the capacity of energy storage) and the storage is almost totally made thanks to the H₂ technology (99% on the mean). This is a direct consequence of the hydrogen devices strong cost decrease. In return, there is a sharp increase of the necessary number of PV panels, quite a doubling, which represents a high required surface.

The main results are synthetized in next paragraph.

3.2.5. Case study n°1: Main results and discussion

The aim of this study was to evaluate Pb-A and Ni-Cd batteries and H₂ storage for a remote PV system on the precise site of *La Nouvelle* in the French overseas island of *La Réunion*. It has been done using a multiobjective optimization methodology taking into account technological and

economic criteria. For both the short and the medium terms, these technologies have been evaluated on relevant scenarios in order to accompany the process of system design and decision making.

In the precise case of *La Nouvelle*, it appears that:

- For the short term, the most economical solution is to use Pb-A batteries coupled with few H₂ bottles as in [Dufo-Lopez & Bernal-Agustin, 2008];
- For the medium term, this is still the cheapest solution but with 10% of profit compared to a solution using Ni-Cd batteries coupled with H₂ storage;
- Coupled with Pb-A batteries, the H₂ is used as a seasonal storage which is not the case when coupling it with Ni-Cd batteries;
- Using Pb-A batteries and H₂ storage leads to use fewer PV panels than when using Ni-Cd batteries and H₂ storage. Indeed, due to the high cost of Ni-Cd batteries, H₂ storage is more utilized than with Pb-A batteries. Thus, due to the efficiency of the global energy chain which is better for the batteries than for H₂ devices, using Pb-A batteries and H₂ leads to a smaller occupied surface than using Ni-Cd batteries and H₂ storage.

So, for the short term, we have to select Pb-A batteries. For the medium term, the choice is quite more complex, since it is then not only cost dependent. For instance, if environmental issues are considered, the use of batteries can be avoided and H₂ storage solution should be preferred. On the contrary, the H₂ storage solution should be avoided when intending to limit the dedicated surface.

These results demonstrate the practical utility of the developed design method. It also has to be noticed that despite the fact that those simulations were based on the *La Nouvelle* concrete case, the results can be extrapolated to many remote areas presenting the same constraints. We can thus assert that in the short term Pb-A batteries have an edge on other analyzed technologies.

In order to further develop the optimization model MOMuS and the comparison of storage technologies for remote systems, we may test other storage technologies (lithium-ion batteries or flywheels for instance), add a cost for building the grid connection which was considered as already existing in our model, test profiles with a smaller time step, or also test other sites and consumer profiles.

3.3. Case study n°2: Minimization of the total levelized cost and the occupied area considering different kinds of PV cells

3.3.1. Case study n°2: Description of the study

Our previous study (see previous paragraph) proposed a multiobjective design of weakly connected systems simultaneously minimizing the total levelized cost and the connection to the grid, while fulfilling a constraint of "end-user satisfaction" which represents the granted risks. Using an in-house multi-objective code based on particle swarm optimization (MOMuS), we pointed up a strong cost advantage when using Pb-A batteries in the short term and a mixed solution for the medium term between Pb-A batteries and GH₂ when coupled to crystalline silicon (c-Si) PV panels.

The objective of this second case study is to extend the previous one by assessing the technical and economic relevance of PV-Battery-H₂ configurations to meet the energy needs identified for the short and the medium term, considering two kinds of PV panels: Heterojunction with Intrinsic Thin layer (HIT) and c-Si cells. The multiobjective design of the system is simultaneously minimizing the total levelized electricity cost and the area occupied by the whole energy system, while fulfilling a constraint of "end-user satisfaction" of 97%. A focus is put here on the occupied area, since it is a major concern when installing PV panels in locations where the place is constrained. The degree of intermittency of the whole system is supposed to be very weak and so the grid connection S_{max} is fixed at 1 kW.

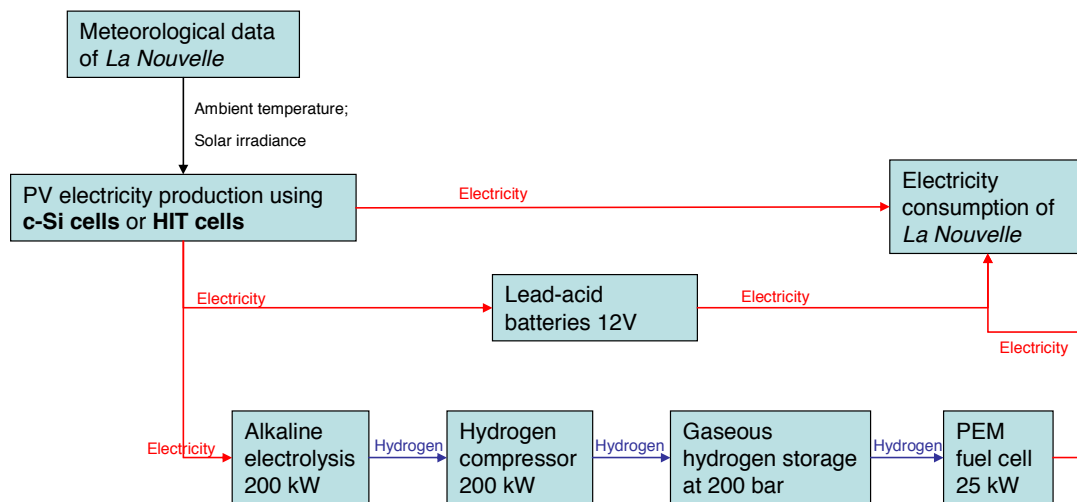


Figure 24: The stand-alone isolated Photovoltaic-Storage system

We studied both c-Si and HIT cells which are more efficient than c-Si but with a higher cost (Cf. Table 7, for more details on these technologies see [Luque & Hegedus, 2011]).

Costs assumptions are issued from an extensive literature review [Cinquin-Lapierre, 2009]. According to the advanced scenario of EPIA [EPIA, 2008], we assumed an annual growth of installed peak power

of 28% between 2011 and 2020, and we considered a learning factor of 22%, which leads the cell cost to decrease from $\text{€}2/W_p$ in 2012 to $\text{€}0.64/W_p$ in 2020 for c-Si; and from $\text{€}2.4/W_p$ in 2012 to $\text{€}0.77/W_p$ in 2020 for HIT respectively.

Concerning the area occupied by one PV panel, this value decrease from 4.00 m^2 for a 100W c-Si panel with an efficiency of 16% to 3.05 m^2 for a 100W HIT panel with an efficiency of 21%. Other technical data are chosen to be the same as the Photowatt-PW6 panel [Photowatt, 2013] (cf. Table 1).

Table 7: Comparison of c-Si and HIT technology performances

Technology		c-Si	HIT
Module power [W]		100	
PV panel efficiency		0.16	0.21
Investment [€/Wp]	2012	2.00	2.40
	2020	0.64	0.77
Area occupied by one panel [m^2]		4.00	3.05

Our goal is to minimize two objectives: TC and the occupied area. The two objectives conflict, since using a high number of PV panels instead of numerous storage technologies is cheaper but more space-consuming. So, solutions we are searching for are again the compromise sets.

We also consider two constraints: one for the consumer satisfaction and another one for a proper use of Pb-A batteries, as defined in the previous cases.

To perform the optimization (once again multi objective and under constraints), we have further developed the MOMuS code, adding the occupied area as an eligible optimization criterion. For a given scenario the MOMuS code modifies the arrangement of the system by changing the number of PV panels, batteries, electrolyzers, hydrogen bottles and PEMFC systems, until reaching optimal solutions. We finally obtain the whole set of solutions that simultaneously minimizes TC and the area, while satisfying the two above constraints.

3.3.2. Case study n°2: computational results – short term and medium term

The computational results are presented for the short and medium terms using the data presented in the previous paragraph and distinguishing c-Si (squares) and HIT (triangles) technologies for the PV panels.

Short term results and medium-term results are presented in Figure 25 and Figure 26. Each point represents an optimal solution (quantities of PV panels and storage devices) for a given cost and surface area. We can observe 5 zones:

- The first one (Zone I, in pink), is the one attainable only with HIT cells. It corresponds to the minimum area attainable.
- The second one (Zone II, in green), is the one attainable only with c-Si cells. It corresponds to the minimum total levelized costs but with a strong increase of the area occupied (around 50%).
- The third one (Zone III, in blue), is the one where HIT should be preferred to c-Si since for a similar cost in zone I, it offers a reduced occupied area.
- The fourth one (Zone IV, in grey), is the one where solutions are not realistic due to the very high number of PV panels and as a consequence the very high occupied area. This zone only appears for the medium-term.
- Finally, the fifth zone is not attainable with these technologies (*TC* or area occupied are too low).

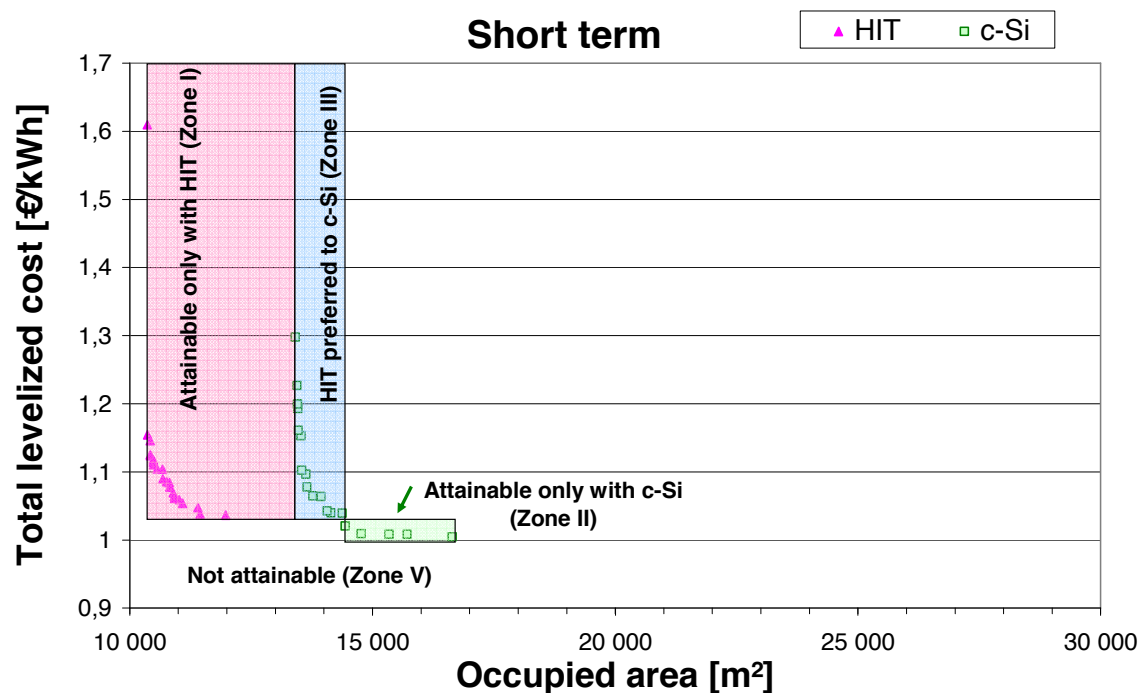


Figure 25: Solutions that minimize both the total levelized cost and the occupied area for c-Si and HIT technologies in the short term

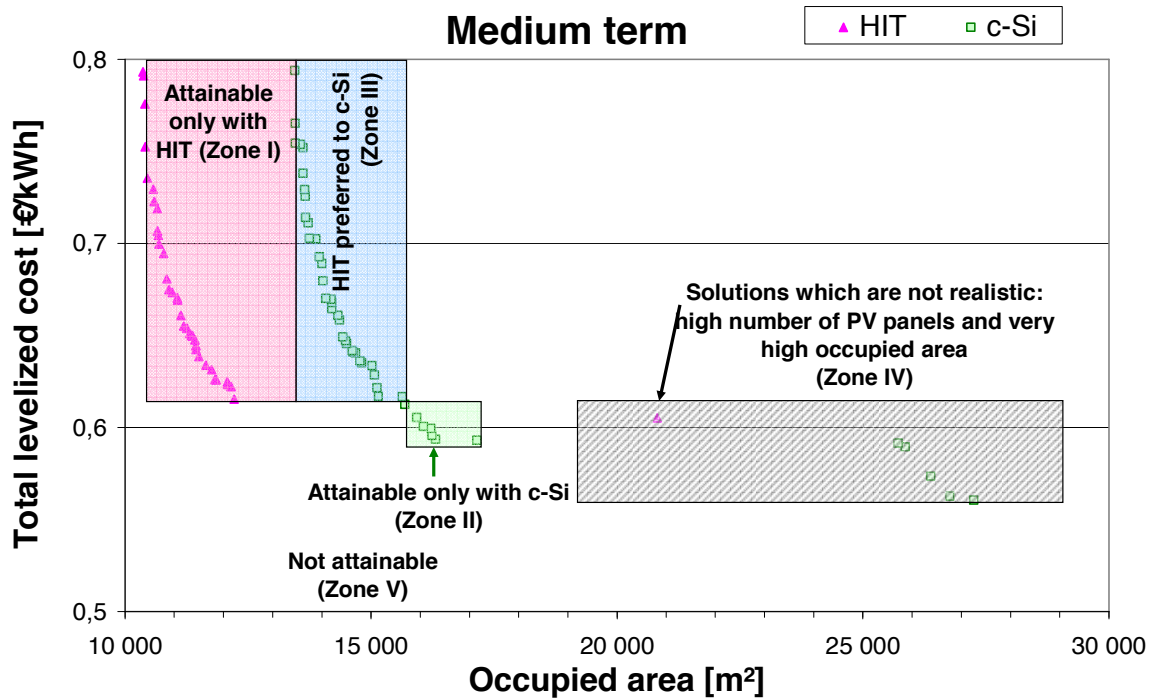


Figure 26: Solutions that minimize both the total levelized cost and the occupied area for c-Si and HIT technologies in the medium term

Concerning the storage technologies, it appears that the storage is principally performed through the Pb-A batteries for the two time frames, the hydrogen storage being considered as a seasonal storage which is coherent with the previous case study and with the literature [Richards & Conibeer, 2007]. The main difference between the short and medium term consists in the higher number of PV panels for the medium term (due to their lower cost) which reduces the needs for storage technologies.

3.3.3. Case study n°2: discussion

The aim of this study was to evaluate, for both the short and the medium terms, different configurations using c-Si or HIT PV cells, Pb-A batteries and hydrogen storage for remote systems for the precise site of *La Nouvelle* in the French overseas island of *La Réunion*. It was done using a multiobjective optimization methodology taking into account technological and economic criteria. The purpose was to simultaneously minimize two objectives: the cost and the occupied area.

This problem is very complex. Simulations enable to obtain the best solutions that simultaneously optimize these two objectives while satisfying the two constraints (a minimum consumer satisfaction of 97% and a constraint on batteries recharge). Each solution is composed of a combination of physical components (PV panels, batteries, etc.).

In the precise case of *La Nouvelle*, it appears that:

- For the short term, there is a strong advantage to use HIT cells rather than c-Si (c-Si can be used to obtain the lowest cost, but with a very important area dedicated to the whole system);
- For the medium term, the discrimination between to the two kinds of PV cells is less obvious (c-Si would be preferred if we want to minimize the cost whereas HIT would be preferred if area is constrained which is the case in *La Nouvelle*);
- Coupled with Pb-A batteries, hydrogen is used as a seasonal storage.

These results demonstrate on another case the practical utility of the developed design method. Again, the results can be extrapolated to other remote areas presenting the same constraints. However, a validation of the simulation results would be necessary, by comparing the conclusions to those obtained with other computational models as well as experimental results.

4. Conclusion of the chapter two

As exposed in the chapter one, PV is meant to have a strong place in the future energy mix. One of the challenges we have to face is its intermittency which could be mitigated thanks to storage devices.

In this chapter, we thus proposed a methodology to assist researchers in defining R&D goals and in designing new renewable systems coupling energy storage to PV. The first step is to choose the right devices both in terms of technological and economic potentials regarding the considered site. Thus the whole system is characterized by different parameters and behavioral equations related to each technology and to environmental data. For a given configuration and given management rules of the energy system, we are able to calculate some variables, such as the total levelized cost of the whole system or the occupied area for instance. We can also include constraints, like the customer satisfaction for instance. The final step is to implement the techno-economic optimization process through a code which operates the simulation for a given configuration of the system and then performs multicriteria optimization under constraints by screening system arrangements (number of each technology device); this leads to the creation of the MOMuS code.

In order to test our developed methodology implemented through the MOMuS code, we performed multi-objective optimizations under constraints considering two different scenarios on an isolated area *Mafate*. The aim of the first case study was to test the relevance of different storage devices considering both the total levelized cost and the degree of intermittency. We conclude that for the

short term coupling Pb-A batteries to a H₂ chain – which is used as a long term storage – leads to a cheaper system than when using a storage coupling Ni-Cd batteries to a H₂ chain. The contrast between these two options is less stressed for the medium term, even if choosing Pb-A batteries still allows to use fewer PV panels than choosing Ni-Cd batteries. The aim of the second case study was to test the relevance of different PV cells considering both the total levelized cost and the occupied area which is a crucial issue in area-constrained locations such as *Mafate*. In this precise case, there is a strong advantage to use HIT cells rather than c-Si for both the short and the medium term, but for the medium term c-Si could be preferred if the cheapest cost of the whole system was targeted without any constraint on the occupied area (which is consequently very important).

This second chapter was centered on a methodology proposal to evaluate the techno-economic relevance of a system composed of PV panels and storage devices in order to take into account the phenomenon of intermittency which can slow down its development. Chapter three hereafter will focus on the comparative analysis and the evaluation of State support measures for the development of PV since there have been very useful for PV development the last ten years in a context of a very aggressive market.

Chapter Three: Comparative analysis and evaluation of support measures for the development of PV: financial estimation and performance comparison of the public support in 5 different representative countries

1. Introduction of the chapter three

As exposed in the chapter One, last decade saw PV technology emerge as one of the most promising technologies for power generation in the world, with an average annual global growth rate of around 47% over the last ten years (between 2002 and 2011) [EPIA, 2011], 75% of the installed capacities being located in Europe. This spectacular growth, despite the high levelized costs of PV electricity generation which were in 2010 in the range of \$333/MWh to \$600/MWh in the Organization for Economic Co-operation and Development (OECD) countries for a 10% discount rate [IEA, 2010a]³, was accompanied by strong national policy supports. Indeed, renewable energy sources (RES) are receiving increasing support worldwide from public authorities because of the environmental advantages they procure in comparison with conventional energy sources, especially when considering the risk of climate change [Nakicenovic & *al*, 2000; Stern 2007].

Thus, many countries have set targets for PV deployment [CPUC 2010; Directive E. U., 2001]. The possibility to achieve them at a lower cost, which was not until now a central issue given that the objectives were limited, has now become a major concern, making it necessary to examine the efficiency of the instruments used to promote PV [Couture & Gagnon, 2010; Menanteau & *al.*, 2003].

³At a 10% discount rate, in OECD countries, the levelized costs of electricity generation are in the range of \$42/MWh to \$137/MWh for nuclear; range between \$76/MWh and \$120/MWh for gas-fired plants; range between \$67/MWh and \$142/MWh for coal-fired power plants with and without carbon capture; and the levelized costs of wind-generated electricity range between \$70/MWh and more than \$234/MWh.

The estimation of the cost of public policies for promoting renewable energy for different countries could help to compare the efficiency of the different economic instruments. An accurate policy would be characterized by significant installed capacities achieved for an acceptable cost. However, such an assessment is a real challenge due to the lack of a common definition for all the ways of subsidies, and to the variability of the data, over time and location [Badcock & Lenzen, 2010]. Notwithstanding this heterogeneity in the bibliographic sources, several studies have been proposed to capture the pros and cons about different types of energy subsidies [Goldberg, 2001; Moor, 2001; Eurelectric, 2004]. In particular, the feed-in tariffs, which are fixed prices guaranteed to an energy producer (per unit of energy produced), are paid a special attention to since they tend to become a widely used tool to support the development of emerging green energy technologies. The debate on the promotion of renewable energy sources is mainly focused on comparing price-driven (feed-in tariffs) and capacity-driven (tradable green certificate) strategies. If the first one consists in setting the price and using Government subsidies, the energy devices quantity being regulated by the market, the latter one relies on the market mechanism to derive a price for a fixed production quantity. For renewable technologies, feed-in tariffs have proven to be the most effective Government incentive program when aiming at boosting the installed capacity [Ackermann & al., 2001; Menanteau & al., 2003 in Gupta & al., 2007]. In the European Union, “well adapted feed-in tariff regimes are generally the most efficient and effective support schemes for promoting renewable electricity” [European Commission, 2009]. In fact, half of the world PV installations were due to feed-in tariff strategies a decade ago [Pieters & Deltour, 1999]. Today, this amount is very likely higher since at least 45 countries had put feed-in tariffs into effect at the national level by the beginning of 2010, not mentioning others that chose to implement them at the State/provincial/territorial and/or municipal levels [Mendonca, 2007; Rickerson & al., 2007, 2008; El-Ashry, 2010 in Mitchell & al., 2011]. In some countries, such subsidies are adapted to follow cost decrease or limit producers' rents. Thus a stepped tariff or a gradually decreasing tariff are sometimes applied to take technological learning into account and to avoid overcompensation [Klein & al. 2010]. There are many different ways to structure the remuneration of a feed-in tariff policy, with varying degrees of success [Couture & Gagnon, 2010]. Moreover, a critical flaw of the feed-in tariff is that it does not induce any cost change on existing polluting technologies, hence not providing any direct motivation to reduce their use [Tamas & al., 2010]. Notwithstanding these necessary adjustments that have to be proposed, the feed-in tariff remains a relevant tool for energy policy.

The aim of this chapter is to present the different public instruments used in 5 emblematic countries for supporting the development of PV technology and to question their efficiency by comparing the estimated total costs of these policies.

The findings which correspond to this chapter have been published through two references [Avril & al, 2012a; Avril & al, 2012b].

Thus, in a first part, a general description of the mechanisms regulating the development of PV systems is proposed. It presents how the demand and supply are acting on the cost reduction of PV systems, through the technological advances engendered, for instance, by the research investments. Then, the public support for PV is assessed for five representative countries from an extensive policy review. At first, we focus on Europe. We firstly consider France, where there have recently been lively debates on the feed-in tariffs which were very high in comparison to other countries at the end of 2010 [France, 2010a] and which were decreased at the beginning of 2011. Then, we focus on Germany, since it is one of the leaders of the global PV market with 7.4 GWp of grid-connected PV capacity installed in 2010, leading to a cumulative installed capacity of 17.34 GWp [IEA, 2011]; this large capacity was facilitated by the Renewable Energy Sources Act [IEA, 2011]. Spain was also chosen for our study due to the spectacular increase of PV new installed capacity in 2008 [IEA, 2009b] and the collapse the years after (17 MW installed in 2009, which is very low compared to the 2.7 GW installed in 2008 [EPIA, 2011]). In a second time, we focus on Japan for its early support of PV, with the MITI⁴ Sunshine Project in 1974 [Watanabe, 1995]. Finally, the US support for PV was analyzed because of their increasing weight on the PV market [EPIA, 2010; EPIA, 2011]. Knowing the cost evaluations of PV supports for these five countries, we will then discuss the specificities looking at the different states of PV development in each country. This has been done considering data from the nineties (when available, depending on the country) until 2010.

⁴ Ministry of International Trade and Industry of Japan

1. Public support measures and cost reduction of PV systems

1.1. On energy policy instruments and technological learning

The objective of this section is to briefly present how public support measures and cost reduction can operate. In 2010, the share of global PV electricity generation was 0.15% [Observ'ER, 2011]. This very low value is due to the fact that PV costs have not met the 'grid parity' yet [EPIA, 2009]. However, PV costs are intended to decrease since this technology is rather young compared to the competitive ones like coal, gas or nuclear power plants (the 'grid parity' is expected in a few years depending on the characteristics of each country according to EPIA [EPIA, 2011b] – this is an optimistic forecast since it only considers the cost of electricity produced thanks to PV panel only and not the whole system as we did in chapter two). In order to favor these cost reductions, Governments chose to support PV deployment so that the national targets of cumulative installed capacities will be reached.

Public support can be categorized into direct and indirect subventions, but also –and we will focus on this distinction – into supply or demand policies. In general, supply policies, also called technology-push, aim at developing the products portfolio; while demand-pull policies correspond to Keynesian policies that act on demand in order to re-launch employment and production [Gallié, 2011]. In the case of new energy technologies, demand-pull policies target the learning-by-doing effect which is particularly marked for PV [Kersten & al., 2011]. Traditionally, R&D support is categorized as a technology-push measure. Public support for R&D is crucial since a major risk of under-investment exists in comparison to what the public interest would be [Arrow, 1962 in Gallié, 2011]. Indeed, financial risks underlie R&D investment [Martin & Scott, 2000 in Gallié, 2011], risks that some companies are unwilling to take. This is especially true for environmental R&D [Jaffe & al., 2002 in Gallié, 2011]. As regards PV, technology-push measures would facilitate the PV cost decrease through the technology improvement (reduction of raw material use for instance) or through breakthroughs (new cheapest technology).

Technology-push measures are most often accompanied by demand-pull ones in order to drive the consumers to adopt the developed innovations, as it will be detailed hereafter as regards PV support measures. Such measures gather feed-in tariffs [Couture & Gagnon, 2010], tax abatement, value added tax (VAT) rate reduction and/or regional aids. The aim is to incite consumers to adopt technologies that are beneficial for the global social welfare, despite their higher costs compared to competing technologies. Technology-push policies usually tend to prevail during the first innovation

phases, while demand-pull measures are predominant at the end when the technology becomes more mature [Dosi, 1988 *in* Gallié, 2011]. Overall both effects may coexist, as suggested by models with the so-called two-factor learning curve [Miketa & Schrattenholzer, 2004]. The two factors are cumulative experience (“learning by doing” [Argote & Epple, 1990; Dutton & Tomas, 1984; Yelle, 1979] and accumulated knowledge (“learning by searching”). As shown by [Neuhoff, 2005 *in* Mitchell & *al.*, 2011], strategic deployment needs to be coupled with increased R&D amounts. In the PV field, the US PV manufacturing program is an example of this policy [Mitchell & *al.*, 2002; Jayanthi & *al.*, 2009 *in* Mitchell & *al.*, 2011].

As a matter of fact, previous studies demonstrated that the reduction in PV cost is the result of diverse factors such as module efficiency, plant size, silicon cost, silicon consumption, yield, wafer size [Nemet, 2006a; Nemet, 2006b]. Based on empirical data on the considered period, the three factors that were identified as most important in explaining cost declines were the plant size, cell efficiency, and the cost of silicon [Nemet, 2006a]. While some of these factors very much depend on the installed PV capacity, others –such as the module efficiency– are more likely the results of the R&D outcomes. Hence, a policy only lying on demand-pull measures would not ensure continuous progress since a part of it can only be brought thanks to R&D.

1.2. Policy tools implementation: example of France

This mechanism is illustrated in Figure 27 for the French case. There have been three waves of targets for PV deployment [PPI, 2002; PPI, 2006; PPI, 2009]. For each new target, the French Government decided to adjust both the subsidies for R&D and the grants for investment. Subsidies for R&D consist in funding photovoltaic power promotion and development activities thanks to: i/ specific funding programs dedicated to PV that are carried out either by the Environment and Energy Management Agency (ADEME), or, since 2005, by the National Research Agency (ANR) and the OSEO agency⁵; ii/ the development of the National Solar Energy Institute (INES) and iii/ competitive clusters dealing with solar power. R&D subsidies are supposed to act on the supply side by helping cost reduction whereas grants for investment are supposed to act on demand by increasing it. Finally, supply and demand are acting on each other since a decrease in prices would lead to an increase of PV modules purchases (change of the supply and demand economic equilibrium along the curves); whereas an increase of demand (and therefore of the module production) would lead to a decrease of module costs (and hopefully prices) according to the learning effect model (supply curve shift).

⁵Public industrial and commercial agency responsible for supporting innovation and growth of SMEs

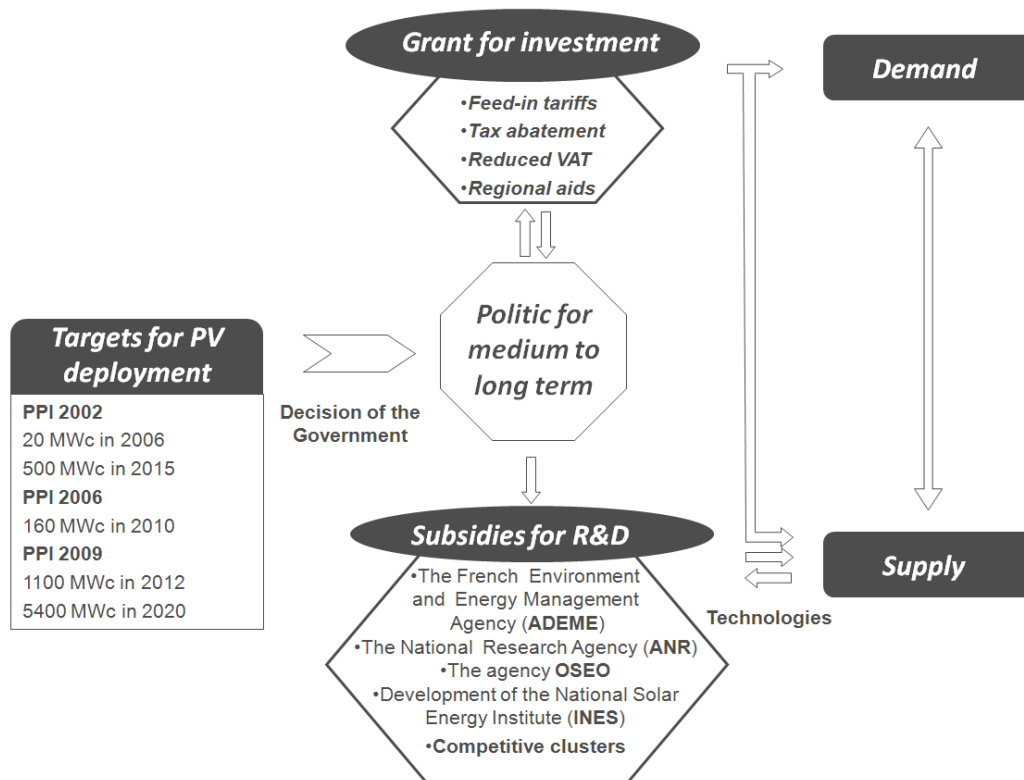


Figure 27: French support system for PV

It is a step-by-step approach, since it is very difficult to link the level of the supports and their effects. The "virtuous cycle" between R&D, market growth and price reduction has been illustrated for PV in Japan [Watanabe & *al.*, 2000]. However, it is very difficult to claim to which extent R&D played a role and to which extent it was boosting the demand. In this context, the use of learning curves can be questioned since it could lead to relate cost reductions to the learning effect only, while a much broader set of influences than experience alone contributed to the rapid cost reductions: knowledge spillovers, market dynamics, etc. As it is highlighted in [Nemet, 2006a], when using learning curves' model strong differences can be observed for the Progress Ratio (PR, for every doubling of capacity production, costs decrease by the Progress Ratio), which is in the range of 0.17 [Unlimited, 2003] to 0.26 [Maycock, 2002]. Besides, the PR should decrease in time due to the increase of maturity and it is quite difficult to carry out cost projections, all the more that these learning curves are based on price data and not cost data [Schaeffer & *al.*, 2004]. Designing policies based on learning curves projections could be misleading; in-depth studies should be carried out on what the cost reduction drivers are, in order to implement the right instruments.

1.3. Toward a protocol for PV support strategies categorization

Before evaluating the level and share of the public support in five representative countries, selected as explained in the introduction, it is necessary to provide a comparative tool between the varying situations of the different countries. A protocol for the categorization of the different PV support types has so to be given. According to the International Energy Agency (IEA) analysis grid, each country presents specificities that naturally lead to a peculiar classification. However, when comparing the different countries, the boundaries between the subsidies classes are vague and they can overlap each other. Thus, some categories of the IEA are quite confusing. For instance, demonstration programs and R&D subsidies are not easy to distinguish. Therefore, we propose a distinction between:

i/ Market incentives: they correspond to the strategies targeting the market.

They include the price-driven approaches:

- Feed-in tariffs: price-driven strategies that guarantee a fixed price;
- Investment subsidies: grants aiming at boosting the demand for PV systems;
- Loans: low interest loans aiming at increasing solar energy capacity;
- Tax reductions;

and the capacity-driven approaches:

- Tradable Green Certificates: a number of certificates is released, their price being derived according to supply and demand balance.

The latest usually apply on “green” energy in general, making no difference between the kind of technology (wind, photovoltaics, etc.). The market incentives that will be identified hereafter will mainly rise from price-driven approaches. Such approaches are usually used by States to reach their objectives of installed capacity.

ii/ Technologies and R&D incentives: they correspond to R&D subsidies and demonstration programs (focused development of PV installations aiming at promoting the solar energy and thus stimulate the market).

When possible, the subcategories are detailed for each country.

Another important point consists in the evaluation of the subsidy costs for the different cases. For the European countries (France, Germany and Spain), the subsidies were calculated as the difference between the electricity tariff and the average market price (fixed by the Energy Regulation Commission (CRE, *Commission de Régulation de l’Energie* in French), in France). We considered the average market price to be of the same order of magnitude for the two other neighbor countries. For Japan and the USA the subsidy costs are given by the IEA. Notwithstanding the discrepancies

between the calculations methods, the obtained results should be coherent and their comparison should be worthwhile.

2. Level and share of the public support in five different countries

2.1. Foreword: the electric mix production in the 5 studied countries

Since we aim at providing a comparative tool between different energy policies, it is interesting to give an overview of each specific electric production mix before detailing the five situations. In

Table 8, we present the electricity production for the five studied countries in 2008 [IEA, 2008a]. Strong differences can be observed, not only concerning the total amount produced, but also concerning the percentage of fossil fuel, nuclear and renewable used to produce this electricity.

Table 8: Electricity production in GWh in 2008, [IEA, 2008a]

	FRANCE		GERMANY		JAPAN		SPAIN		USA	
coal	27 231	5%	290 645	46%	288 253	27%	49 973	16%	2 132 596	49%
oil	5 825	1%	9 244	1%	139 171	13%	18 002	6%	57 776	1%
gas	21 884	4%	87 654	14%	283 153	26%	121 561	39%	910 589	21%
biomass	2 116	0%	19 851	3%	15 079	1%	2 473	1%	50 201	1%
waste	3 776	1%	9 368	1%	7 309	1%	1 564	0%	22 190	1%
nuclear	439 468	76%	148 495	23%	258 128	24%	58 973	19%	837 804	19%
hydro	68 325	12%	26 963	4%	83 295	8%	26 112	8%	281 995	6%
geothermal	0	0%	18	0%	2 752	0%	0	0%	17 014	0%
solar PV	41	0%	4 420	1%	2 251	0%	2 562	1%	1 572	0%
solar thermal	0	0%	0	0%	0	0%	16	0%	878	0%
wind	5 689	1%	40 574	6%	2 623	0%	32 203	10%	55 696	1%
tide	513	0%	0	0%	0	0%	0	0%	0	0%
other sources	0	0%	0	0%	0	0%	307	0%	788	0%
Total	574 868		637 232		1 082 014		313 746		4 369 099	

In France, the electricity mix was composed in 2008 of 76% of nuclear power plants, 10% of thermal power plants (oil, natural gas and coal) and 14% of renewable energies (of which 12% are hydraulic plants) [CEA, 2009]. Thus GHG due to electricity production are very low in France.

In 2009, the German electricity mix was composed of about 60% fossil fuels (about 47% coal and 12% natural gas), 30% nuclear (meant to decrease in the years to come) and 10% renewable energies (mainly hydraulics and to a lesser extent wind power) [Germany, 2010]. About one percent of the total generation came from local PV installations.

Japan has little domestic energy resources and is only self-sufficient for 16% of the energy. Thus, Japan is one of the major exporters of energy equipment and has a strong energy research and

development program that is supported by the Government, which domestically pursues energy efficiency measures in order to increase the country's energy security and reduce the carbon dioxide emissions.

The structure of the Spanish electricity production was in 2008 about 61.9% fossil fuels, 18.2% nuclear and around 19.6% renewable energies (8% hydraulic, 9.8% wind power, 1% biomass and 0.8% solar), producing 322.6 TWh [Spain, 2010a].

In 2007, Japan had 279 GW of total installed electricity generation capacity, the third largest in the world behind the US and China. Of the country's 2008 total electric power generation of 1,015 billion kWh, 67% came from conventional thermal sources, 24% came from nuclear sources, 7% from hydroelectric sources, and 2% from other renewable [Japan, 2010b]. The disaster of Fukushima in March 2011 changed this distribution, as subsequent to it, the nuclear power plants have gradually been stopped. Although Japan accounts for the most important electricity consumption in OECD Asia, it has one of the lowest electricity demand growth rates in the region, projected at an average of 0.7% from 2007 through 2018 by the Federation of Electric Power Companies of Japan. Wind and solar power are being actively investigated in the country and the installed capacity from these sources has increased in the recent years to about 1.5 GW in 2007, from 0.8 GW in 2004. However, they continue to account for a relatively small share of generation at this time.

The structure of the US electricity production was in 2008 about 71.3% fossil fuels (mainly coal with 48.2% and then natural gas with 21.4% - we can notice than this repartition recently changed due to shale gas), 19.6% nuclear and around 9.9% renewable energies (6% hydraulic, 1.4% wind power, 1.4% biomass, 0.4 geothermal and 0.02% PV and solar thermal), producing 4,119 TWh [USA, 2010].

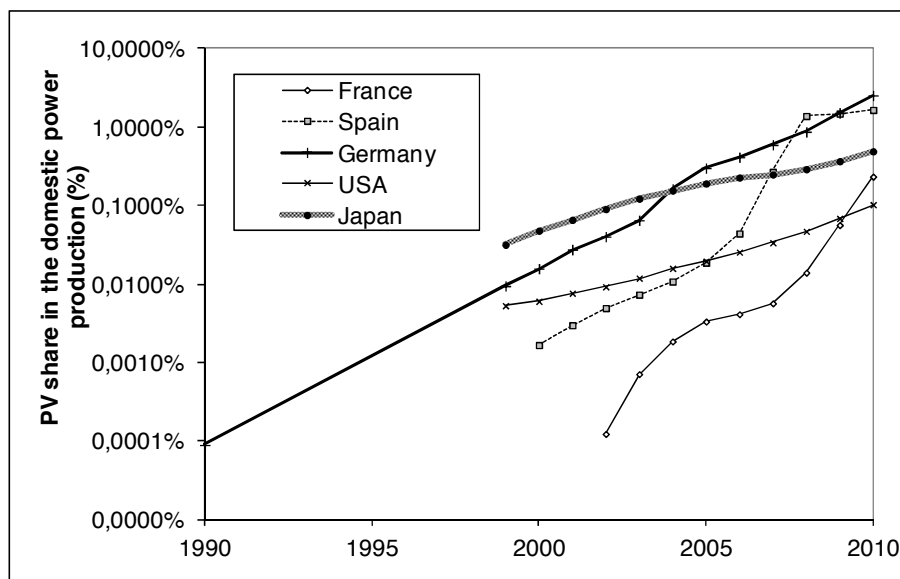


Figure 28: Evolution of the PV share in the total electricity production, according to the country [OECD, 2012]

According to the diverse situations of these countries, motives for developing photovoltaics can be varied: increasing the share of renewable energy in the electricity mix to achieve the European objectives and reduce the CO₂ content of electricity production, develop a new market and eventually local economic activity, reduce the energy dependence to fossil imports.

As it is depicted on Figure 28, the considered countries demonstrated enough will to implement PV capacity that can today supply between 0.1 to 2.5% of the domestic electricity production. We will try assessing the countries' policy efficiency that we define as the ability to install significant PV capacity at an acceptable cost. To do that, four indicators will be proposed (see section 3 - Comparison of the different policies to promote PV):

- the annual expenses compared to the installed capacity the same year;
- the average cost of the installed capacity;
- the average cost of the produced energy;
- the gap to grid parity.

These indicators will be calculated for each year and pursue different objectives. The first one provides a measure of the policy durability, which is one condition for a new market development. Indeed, investors need visibility on the market outlook. By assessing the average cost of the installed capacity, we can approach the financial investment that increasing the photovoltaic power implies. Finally, the evolution of the average MWh cost and its gap to reach the grid parity can propose a measure to evaluate the efficiency of the policy in achieving technology cost reduction.

2.2. In Europe: a predominance for demand-pull measures

2.2.1. French support for PV

French support to PV technologies began in the early 1990s with the electrification of isolated areas where the connection to the grid was very costly. On-grid installations have only been subsidized since 1999, the total installation price being subsidized with rates varying between 35% and 80% until 2000, the average rate being reduced to 35% in 2001 and 2002, and to 30% in 2003 and 2004. These subsidies were replaced in 2005 with a tax abatement of 40% on the equipment price, reassessed to 50% in 2006 and guaranteed until 2012 [France, 2010b]. This tax was once more reassessed and decreased to 25% on the 29th of September 2010, to 22% in 2011 and to 11% in 2012 [France, 2010c]. Indeed, this rate was too high, leading to a very high support of the French Government and creating a mask effect (even if the costs were decreasing, the prices remained still). The revision frequency of the policy questions its relevance (see Figure 29 p.89).

Concerning the feed-in tariffs, they appeared in 2002 to accompany objectives of the Investment Programming for electricity production lasting several years (PPI, *Programmation Pluriannuelle des*

Investissements in French) which fixed a goal of 20 MWp installed at the end of 2006. With the 2006 PPI and the 2009 PPI⁶, four new ordinances modified these tariffs to meet new objectives and to avoid speculative bubble (see Table 9). In particular, we can observe that there are more and more subdivisions in order to take into account the different situations (location, kind of installation, level of power, etc.). The last ordinance even takes into account the amount of new installations connected to the grid by adjusting the FIT each quarter in order to avoid a too quick development. We can also notice that the changes are in quicker succession, which cannot be convenient for investors. Note that all these feed-in tariffs had been fixed for a 20 year period.

⁶The 2006 PPI fixed a goal of 160 MWp installed in 2010 and 500 MWp in 2015; the 2009 PPI fixed a goal of 1,100 MWp installed in 2012 and 5,400 MWp in 2020.

Facilities	Roof integrated										Simple integration			Others					
	Main home					Large roofs								Corsica, Overseas Departments and Mayotte		Metropolitan France			
	Educational and health buildings		Others(industrials and cultivators)																
	0-3kWc	3-9kWc	9-36kWc	36-100kWc	0-36kWc	36-100kWc	0-9kWc	9-36kWc	36-100kWc	0-36kWc	36-100kWc	0-36kWc	36-100kWc	30.50 €/kWh	15.20 €/kWh				
March 13, 2002, Ordinance	No differentiated feed-in tariffs for integrated PV																		
July 10, 2006, Ordinance	55 €/kWh													40 €/kWh		30 €/kWh			
January 12, 2010, Ordinance	58 €/kWh					50 €/kWh					42 €/kWh			40 €/kWh		31.4 to 36.74 €/kWh (from South to North)			
August 31, 2010, Ordinance	58 €/kWh	51 €/kWh				51 €/kWh					44 €/kWh			37 €/kWh		35.2 €/kWh		27.6 to 33.12 €/kWh (from South to North)	
March 5, 2011, Ordinance	41.63-46 €/kWh	36.43-40.25 €/kWh	26.09-28.83 €/kWh	36.74-40.6 €/kWh	26.09-28.83 €/kWh	31.86-35.2 €/kWh	27.47-30.35 €/kWh	26.09-28.83 €/kWh	27.47-30.35 €/kWh	27.47-30.35 €/kWh	26.09-28.83 €/kWh	27.47-30.35 €/kWh	26.09-28.83 €/kWh	12 €/kWh					

Table 9: Evolution of the feed-in tariffs in France⁷

⁷ From the publication of the ordinance of the 5 march 2011, the supervision level in tariff will be reviewed at the end of each quarterly period. This will be based on the sum of the power projects that have been the subject of a complete connection in the previous three months elapsed. Depending on the volumes presented for each segment, the purchase price for the next quarter would be reduced to 9.5% (maximum tariff for less than 5MW connected and minimum tariff for more than 65MW connected).

Knowing the annual growth [IEA, 1999-2011] which led to a cumulative installed capacity of 1,054 MWp in 2010 (2,500 MWp in 2011), we estimated the amount of the PV support for both subsidies and tax reductions, and for the feed-in tariffs. The amounts of the annual subsidies for R&D are provided by the International Energy Agency [IEA, 1998-2010c] until 2010 (the value is unknown in 2009). The results are gathered in Figure 29.

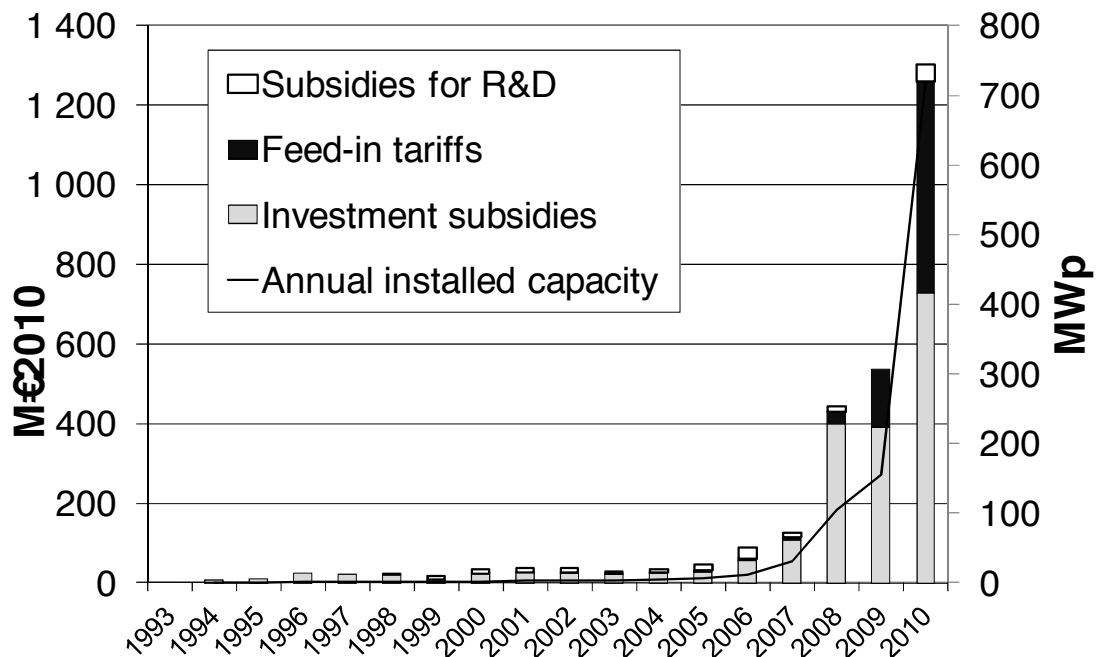


Figure 29: Annual installed capacity [MWp] and annual costs of the French policy to support PV [M€2010] from 1993 to 2010 (R&D unknown in 2009)

What is very important to notice is that, until today, subsidies and tax reductions have weighed a lot on the total PV support (more than 93% in 2008). Subsidies for R&D have fluctuated around the mean value of 11 M€ per year since 1998, the value of 2010 being more important, higher than 40 M€. Concerning the feed-in tariffs, their weight is fast increasing since they are established for a 20 year period and they will play the major role in PV supports in a few years. This effect can already be observed for the year 2010.

Let us focus on them. In the particular case of France, the feed-in tariffs are paid by the electricity consumers *via* the public electricity contribution (CSPE, *Contribution au Service Public de l'Electricité*

in French)⁸; what is really paid in the contribution is the cost overrun between the feed-in tariff paid to the PV producers (multiplying the amount of kWh that is produced by the current tariff) and the weighted average market price (PMMP, *Prix de Marché Moyen Pondéré* in French). These two amounts are represented annually in Figure 30. To obtain this figure, we assumed: i/ as regards the annual installed capacity, an annual growth of 500 MWp until 2020 divided into three parts (150 MWp for the individual installations, 200 MWp for large roofs and 150 MWp for ground-based systems) as it is advised by [Charpin & al., 2010]; ii/ as regards the tariff, a mean tariff for each category (individual installations, large roofs and ground-based systems) assuming that the ordinance of March 5th 2011 is kept until 2020 and only considering the contracts implemented before this date; iii/ a decrease of 10%/year of the previous tariffs; iv/ an inflation rate of 2% (consistent with what was observed recently). The difference between the cost of the feed-in tariffs paid to the PV producers, which is commonly calculated by people who are against the feed-in tariffs, and the real cost is about 60% on average. Thus, the maximum annual cost really paid in the public electricity contribution due to the PV feed-in tariffs will be around 1 billion € in 2020 leading to a total amount of 23.6 billion €-2010 during the period 2002-2040 (the 20-year feed-in tariffs will end in 2020). Of course, when these amounts are discounted, their burden is lowered since future expenses are diminished. The influence of the discount rate on the total amount paid in the contribution to support PV feed-in tariffs can be seen in

Table 10.

⁸France collects a public goods charge, the *Contribution au Service Public de l'Électricité* (CSPE), from electricity consumers, in order to pay for renewable energy, fossil-fired combined heat and power, electricity access continuity over the French territory, and for social tariffs.

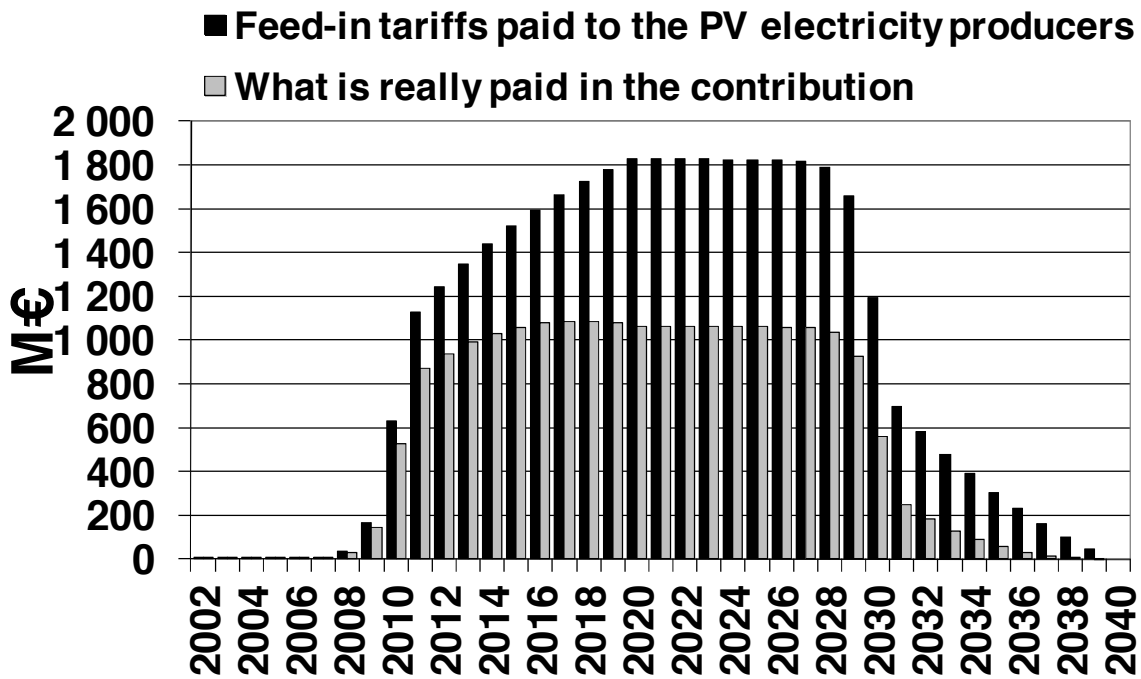


Figure 30: Annual costs of the French PV feed-in tariffs paid to the PV producers (multiplication of the number of kWh produced by the current tariff) and annual costs of what is really paid via the public electricity contribution

Table 10: Impact of the discount rate on the public electricity contribution during the period 2002-2040 due to PV feed-in tariffs

Discount rate	0%	5%	8%	10%
Contribution amount (G€2010)	23.6	14.5	11.4	9.9

2.2.2. German support for PV

The German Government sponsorship of renewable energy was initially spurred by energy security concerns during the 1970s. The energy crises of 1973-74 and 1979-80 had severe economic impacts on Germany as on most other industrialized countries; consequently, renewable energy sources were promoted as a potential means of alleviating the risks associated with high fossil fuel import dependence. Germany has been a proponent of international policy action to address climate change and has adopted a broad set of domestic actions to curtail its GHG emissions. Consequently, renewable energy sources and accelerated deployment of renewable energy technologies are seen by the German Government as playing a central role in meeting its voluntary GHG reduction goals.

Support for PV at the German national level has progressed through 3 phases: the 1,000 solar roof program (rebates) from 1990-1995, the 100,000 solar roof program (soft loans) initiated in 1999, and the Renewable Energy Source Act (premium tariffs) implemented on April 1, 2000 [IEA, 1998-2009]. Each of these phases is detailed below.

Germany became the first country worldwide to launch a major solar installation initiative when it announced the 1,000 Solar Roof Program in 1989. This program provided rebates for up to 70% of system costs for installations in the range of 1 to 5 kW for the main or the secondary homes. This program ended in 1993. Other measures have been introduced at the same time, like VAT exemption or some subsidies attributed by each Land.

The 100,000 Solar Roof Program was implemented in January 1999, with an initial goal of installing 300 MW by 2004. Funded with 560 million €, the program provided 10-year low interest loans (1.91% in 2001) with no money down and no interest payments for 2 years. This financing package corresponds to a subsidy of roughly 20% [Reinmüller & al., 2002].

The Renewable Energy Source Act, the new and improved version of Germany's original feed-in law (which has been in place since January 1991) took effect in April 2000 (Law EEG - *Erneuerbare Energien Gesetz* in German - Renewable Energy Sources Act⁹). Under the old feed-in law, PV and wind shared the same tariff, around €9/kWh. While this tariff was sufficient to spur massive wind development throughout Germany, it was insufficient to support a similar rate of PV development, given its higher cost. The Renewable Energy Source Act increased the PV tariff nearly 6-fold to €0.51/kWh for a twenty year period for each kind of installation (ground-based or roof-top devices). In 2004, the EEG law was modified and the tariffs have now to decline by 5% each year to encourage cost reductions. In addition, tariffs are discriminated knowing the localization of the installation and its power.

Finally, strong decreases in the tariff have been implemented in 2010 (about ten percent in January and about fifteen percent in April). The evolutions of the feed-in tariffs are gathered in Table 11. Recently, the decrease of the FIT was even greater. It reached 24% in 2011, when the installed capacity exceeded 7.5 GWp.

⁹ Since 2000, the Law on Renewable Energy aims to:

- sustainable development of energy supply in the interests of climate protection, nature and the environment;
- contribution to conflict prevention with fossil fuels to challenge and further technological development of electricity production from renewable energy sources;
- technological development;
- meet the objectives of renewable energies in the electricity supply, 12.54% in 2010 and 20% in 2020.

Table 11: Feed-in tariffs for photovoltaic electricity in Germany [€/kWh]

	Roof-Top Tariff				Ground-Based Systems	Decline
	<30kWc	<100kWc	<1MWc	>1 MWc		
EEG 2000	0.51					5% each year from 2002
EEG 2004	0.574	0.546	0.54		0.457	5% each year from 2005
EEG 2010	0.4301	0.4091	0.3958	0.33	0.3194	At least 10% in 2010, and 9% from 2011 onwards for freestanding facilities as well as for roof systems over 100kW. For roof systems up to 100kW, the reduction will be 8% in 2010 and 9% from 2011.

Knowing the annual growth [IEA, 1998-2009] which led to a cumulative installed capacity of 17,370 MWp at the end of 2010, we have estimated the amount of the PV supports for both investment subsidies and loans, and for the feed-in tariffs. The amounts of the annual subsidies for R&D are provided by the International Energy Agency [IEA 1998-2010]. The results are gathered in Figure 31.

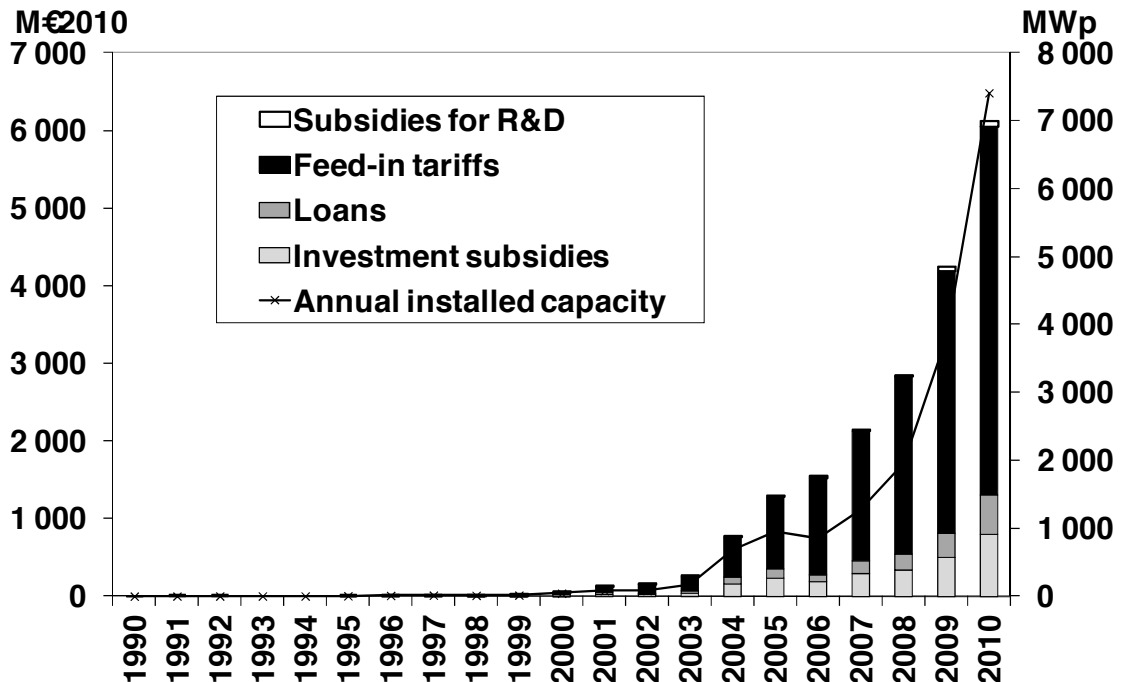


Figure 31: Annual installed capacity [MWp] and annual costs of the German policy to support PV [M€] from 1990 to 2010

We can observe that there has been a strong acceleration of the installed capacity with the creation of the feed-in tariff, with 44 MWp installed in 2000, to exceed 7,000 MWp installed in 2010. The feed-in tariffs have quickly taken a significant part of the policy costs, and they represented more than 77% of the total amount spent to promote PV in 2010. They also lead to have a high cumulative installed capacity, but this will generate an expensive cost in the future (which explains the recent decrease of the feed-in tariffs).

Concerning the public support for R&D, the amount is in the same order of magnitude as in France, around one dozen million € in 2008 with an increase in 2009 and 2010 (around 64 M€ each year), but in the case of Germany, it represents only one percent of the annual cost to support PV.

2.2.3. Consequences of the feed-in tariffs on the electricity prices in France and Germany

The aim of this subsection is to present the impacts of the feed-in tariffs on the electricity bill for both France and Germany. The findings which correspond to this chapter have been published through [Avril & al, 2012c].

In France, let us recall that the overpricing generated by the difference between the feed-in tariffs and the weighted average market price is paid by the electricity consumers through the *Contribution au Service Public de l'Electricité*. This tax is proportional to the amount of electricity consumed (albeit with caps for large industrial consumers). It also includes additional costs resulting from the tariff equalization for non-interconnected metropolitan network areas as well as the establishment of electricity pricing as a staple good.

If we study the load distribution since 2003 based on the data provided by the CRE [CRE, 2003-2012], we can remark that the first historic item of expenditure concerned the purchase obligation related to cogeneration. Annually the amount was between 600 and 1,000 M€, fluctuations are linked to changes in volumes concerned and those of fossil energy prices. However, from 2008, the costs related to standardized tariffs were most important. While lower than € 400 million in 2003, the amount of 2010 was estimated at € 970 million. This is related both to the sharp increase in fuel prices and that of final consumption. From 2012 and then, it is now support measures via feed-in tariffs of solar PV which are significantly playing on the electricity bill, with 1.4 billion € of a total of 4.3 billion € for the whole CSPE. Solar PV accounts for nearly 80% of the observed CSPE increase between 2010 and 2012. Finally, note that the social provisions, though continuously rising, little weigh on the whole amount.

In the future, the cost of renewable energy will continue to make the CSPE increase. The weight of the feed-in tariffs for photovoltaic electricity is expected to increase, but in 2020 the first cost item should be predominantly the purchase prices for electricity generated by offshore wind turbines according to the estimations of the CRE [CRE, 2011] (2.5 billion € for PV solar and 3.4 billion € for offshore wind, for a total of 7.5 billion € only for feed-in tariffs for the renewable energies in 2020 against 2.2 billion € currently). Let us recall that nowadays the total sales and distribution of electricity in France is about 40 billion € annually.

These increases strongly impact the amount of CSPE. Initially set at €3/MWh in 2002, CSPE was reassessed at €3.3/MWh in 2003 to €4.5/MWh in 2004. Between 2004 and 2011, no new order had changed its value despite the recommendations of the CRE upward or downward. It was only in 2011 that the CSPE was amended to increase to €7.5/MWh, value lower than the one recommended by the CRE which was €12.9/MWh. This increase was achieved through the Finance Act 2011 [Legifrance, 2010] passed by the Parliament which establishes the following principles:

- Automatic recovery of CSPE proposed by the CRE level in case of absence of Minister's order;
- Limited to a maximum of 3 euros per MWh compared to the level of the previous year.

Again in 2012, the CSPE increased of €3/MWh - the maximum allowed by the Finance Act 2011 - (+ €1.5/MWh biannual increase - see Figure 32) and reached the value of 10.5 €/MWh. Despite this significant increase, the value of the CSPE was below the one calculated by the CRE, which was of €13.7/MWh taking into account in the forecasted costs.

Thus, annual increases being limited to €3/MWh, the CRE forecasts increases until at least 2015, meanwhile EDF considers a return to the balance of its accounts to 2015-2016.

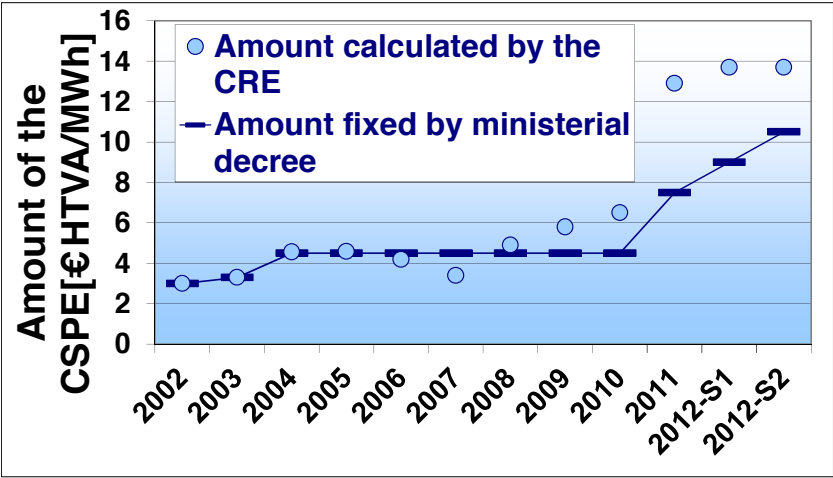


Figure 32: CSPE amount calculated by the CRE and fixed by ministerial decree (2002 - 2012) (from [CRE, 2002-2011])

Germany is the European leader in on-shore wind capacity installed and solar photovoltaic with 29 GW and 25 GWp installed in late 2011 respectively. For comparison, the figures for France are 6.6 GW of wind and 2.7 GWp solar PV installed in late 2011.

This was possible thanks to the application of the EEG law.

Renewable energies are promoted through attractive purchase tariffs. They relate to hydropower, including energy wave, tidal, energy marsh salinity gradient energy and currents, wind energy, solar energy, geothermal energy, energy from biomass including biogas, gas deposition and gas cleaning and biodegradable parts of household and industrial waste.

The annual electricity generated via renewable energies in Germany thanks to the EEG is around 90 TWh for an amount of € 16.7 billion (electricity price is €177/MWh on average). The projections to 2016 give productions of 100 TWh for a total of € 19 billion (electricity price would be €190/MWh on average).

The amounts spent annually were first mainly due to the development of wind power, but since 2009 it has been solar photovoltaics which have weighed most heavily on expenditure.

Note that these amounts are primarily paid by individuals (the EEG value for the individuals in 2012 is very high and amounts to €35.92/MWh), the industrials have contributed since 2010, with an amount of 10% of the EEG value for an industrial consuming between 1 and 10 GWh, 1% of the EEG value for an industrial consuming between 10 and 100 GWh and €0.5/MWh for large consumers, that is to say, those consuming more than 100 GWh. It should be noted that the number of industrials benefitting from a special rate rose sharply from 813 in 2011 to 2,083 in 2012, i.e. over doubled. This alerted the European Commission that has launched an investigation on unauthorized State aid.

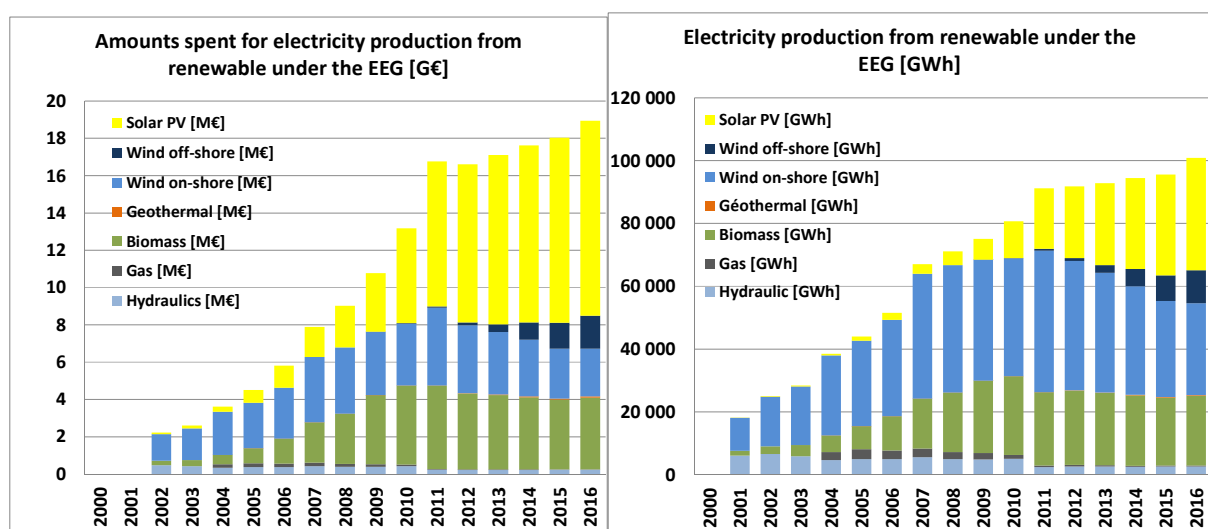


Figure 33: Annual amount of electricity generated via renewable energies in Germany in relation to the EEG [GWh] (left figure) and corresponding expenditures [G€] (right figure), from [EEG, 2013]

For comparison, it is interesting to have a look at the past and future of the CSPE and the EEG overcost.

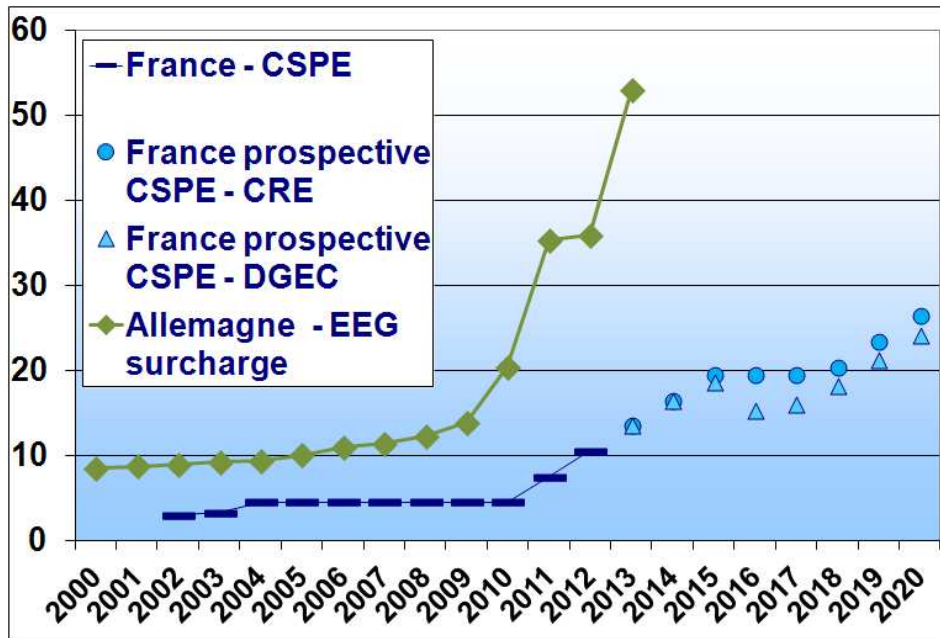


Figure 34: Comparison of the amount of CSPE in France and the overcost due to EEG in Germany (€/MWh) - historical data between 2000 and 2012, projections to 2020, from [Sénat, 2010; EEG, 2013b]

In the case of France, the expected developments reported in the Senate Report No. 667 [Sénat, 2010], whether conducted by the CRE or by the DGEC, lead to a value of the CSPE comprised between €24.2 and €26.4/MWh in 2020, an increase of €2/MWh per year on average over the next eight years to reach a total of about 10 billion € per year in 2020.

For a French household that consumes about 6 MWh per year, the CSPE represents:

- €60/year in 2012 (€30/year due to renewable support),
- €150/year in 2020 (of which €100/year due to renewable support).

In the case of Germany, the amount of the EEG is higher although it only takes into account the RES. This gap is explained by the difference in the amount of RES installed (between 4 and 5 times more installed wind power and 9-10 times more solar power installed). The EEG has been high since 2009, when photovoltaics began to grow very significantly. The annual expenditure in 2016 should be around 19 billion € [EEG, 2013b]. In the coming years, Germany intends to reduce the economic weight of this massive introduction of renewable energy thanks to the expected decline in subsidies

(the price of electricity increases, the difference between the weighted average market prices and the purchase decreases) or suppression of these feed-in tariffs (the latest negotiations of the new Government forecast a suppression of the feed-in tariffs for PV when there will be 52 GWp installed).

Anyway, this massive increase of renewable energy begins to bear significantly on the price of German electricity. For a German home, the annual contribution to renewable is now 185 euros per year and the growth trajectory is not known. Recall that German households consume almost twice as less electricity than the French because electric heating is less developed. On the other hand, they consume 30% more gas.

2.2.4. Spanish support for PV

Spain support to PV market was belated compared to other countries and only began in 1999 with the *Plan de Energías Renovables en España* (PER) 1999-2010 which fixed a target of 20 MWp for off-grid installations and 135 MWp for on-grid installations in 2010. The real boom of the Spanish PV market only appeared with the very attractive feed-in tariffs set by the Royal Decree 436/2004, dated 12 March 2004. Then, there was a drastic market expansion between 2006 and 2008 with the Spanish Government's approval of the PER for 2005 – 2010 in August 2005. The objectives were to cover 12.1% of Spain overall energy needs and 30.3% of total electricity consumption with renewable energy sources by 2010. So, in 2007 the Royal Decree 661/2007 passed with an increased cap of 1,200 MW for PV installations and triggered a run on permits to install multi-megawatt free-field solar photovoltaic electricity systems (the tariff was €c44.04/kWh for installations up to 100 kWp for 25 years, €c41.75/kWh for plants delivering 100 kWp to 10 MWp and €c22.94/kWh for plants delivering up to 50 MWp). Thus, in 2008, Spain was the biggest PV market due to the almost five-fold increase from 560 MW in 2007 to about 2.7 GW in 2008 [EPIA, 2010]. This was more than twice the expected capacity and was due to an exceptional race to install systems. This development led to the revision of the solar PV legislation in 2008, and the new Royal Decree 1758/2008 which was approved on 26 September 2008. Now there is a distinction between building-integrated installations (roofs or fronts) and ground based power plants as the two applicable tariff groups. The feed-in tariff for the first group was then €c34/kWh for applications up to 20 kWp, followed by €c32/kWh for installations in the 20 kWp to 2 MWp range. Lastly ground-based power plants were paid €c32/kWh up to a capacity of 10 MWp. These different tariffs apply for 25 years and the maximum annual installed capacity qualifying for the feed-in tariffs was capped for each kind of application. The 2009 ceiling was 500 MWp (including 233 MWp from ground-based power plants), 502 MWp in 2010 (including 207 MWp from ground based power plants) and 488 MWp in 2011 (including 162 MWp

from ground based power plants). Despite this decrease in 2009, Spain's feed-in tariffs rates were fairly high. In 2010, the decree 14/2010, from December 23 retroactively limited the maximum number of hours of PV installations that have the right to receive feed-in tariffs; it depends on the solar irradiation and the climatic zone the PV system is located in. As a compensation, the duration of the feed-in tariffs was extended from 25 years to 28 years. To accompany this decree, new lower feed-in tariffs were defined. Indeed, the country's industry ministry said that guaranteed prices for large, ground-based new PV plants would be cut by 45%, while those for large roof installations would drop by 25% and for smaller ones by 5%. *"These percentages reflect the improved technologies and cost reductions that have occurred in the photovoltaic sector, which suggests the gains should be transferred to consumers while allowing attractive rates of return for investors"*, the ministry said [Spain 2010b]. Finally, since January 2012, the feed-in tariffs have been in the range of €0.122-0.266/kWh [PV-tech, 2012].

This new legislation effectively curbed the growth of Spain's capacity which reached 4,200 MWp installed by the end of 2011.

Some investment subsidies have also been created in order to promote PV systems, but they are insignificant in comparison to the feed-in tariffs. About 25-35% of the equipment price was subsidized before 2004. After the PER, only 22% of the off-grid installations were subsidized whereas on-grid installations were no more subsidized (subsidies were replaced by reductions: revenue from PV is not taxed).

Knowing the annual growth [IEA 1998-2009, EPIA 2010] which led to a cumulative installed capacity of 4,200 MWp in 2011, we have estimated the amount of the PV supports for both investment subsidies and for the feed-in tariffs. The results are gathered in Figure 35.

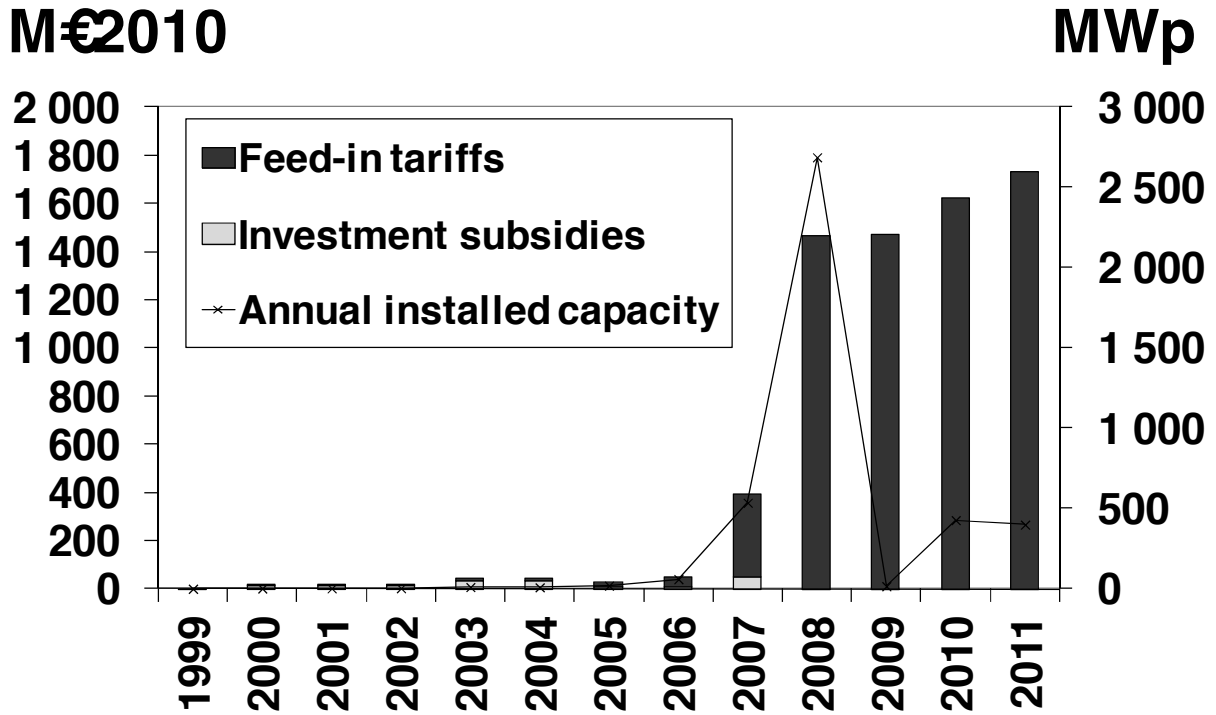


Figure 35: Annual installed capacity [MWp] and annual estimated costs of the Spanish policy to support PV [M€] from 1999 to 2011 (R&D excluded)

The amounts of the annual subsidies for R&D are not provided by the International Energy Agency, contrary to the case of the other studied countries. It is only mentioned that public budgets for R&D come from i/ the European Commission (9 projects financed for 41.6 M€ since 2003); ii/ national budget from the Ministry of Education and Science and by the Ministry of Science and Technology; and iii/ regional budget from the 17 autonomous communities. The total amount dedicated to R&D in 2008 is estimated to 12 M€, which is of the same order of magnitude that for the other European countries (France and Germany) [Spain, 2009].

In Figure 35 we can observe that there has been a big acceleration of the installed capacity with the creation of the 2007 feed-in tariff, with nearly 2,700 MWp installed in 2008, and a strong deceleration with the new 2008 feed-in tariffs with less than 100 MWp installed in 2009. This shows the quick adaptation of the market to these policy incentives. The fact that the Government was forced to create retroactive measures clearly indicates that the installation capacity boom was not anticipated, which resulted in difficulties for the PV sector (quick market growth followed by sudden market contraction).

Impact of the subsidies for the solar photovoltaic on the Spanish electric system.

Although representing only 10% of renewable electricity generation, solar photovoltaics have concentrated the bulk of aid, creating a bubble. Moreover, despite the rising costs of producing electricity inherent to these developments, the Spanish regulated tariff for electricity (TUR) remained relatively low, creating a 30 G€ tariff deficit in 2013 (it amounted to 24 G€ in 2012).

The electricity deficit amortization fund has already securitized approximately € 25.2 billion, which means that every Spaniard must pay, by 2027, securities issued, with an average interest rate of 4.48%. "Every Spaniard is 600 euros in debt for the supply of electricity." [Enerpresse, 2013c]

2.3. In Japan: a coexistence of technology-push and demand-pull measures to support PV

The Japan national budgets for PV systems focus on R&D, demonstration programs and market incentives [Ikki & Tanaka, 2003; Ikki & Matsubara, 2007-2008-2010; Yamamoto & Ikki, 2011].

First aids began in 1974 especially for R&D on residential rooftop systems. In 1992, buy-up system for PV system-generated surplus power started at selling price by electric utilities. From 1994, with the launch of many demonstration programs that were administered by the New Energy Foundation (NEF), part of the Ministry of Economy, Trade, and Industry (METI), the development of PV systems has strongly increased. The main demonstration programs that were implemented are:

- "Residential PV System Dissemination Program" (1994) which aimed at subsidizing the PV installation cost for individuals on the condition that they understand the significance of PV introduction and provide the operation data of their PV systems;
- "PV Field Test Project for Industrial Use" (1998). This program gave half of PV installation cost subsidies to private companies, local public organizations and other organizations. PV systems, especially 10-100 kW systems, have been installed in schools, welfare facilities, manufacturing plants, warehouses, office buildings, private facilities, and so on;
- "Support Project for Local Efforts to Introduce New Energy" (1997) aimed at accelerating new energy introduction by supporting the regional projects that Governments established for new energy. PV systems with 50 kW output and over were subsidized up to half of the system installation cost;
- "Financial Subsidy Project for Entrepreneurs Introducing New Energy" (1997) aimed at accelerating new energy introduction by supporting the industrialists. Eligible for guaranteed debt or subsidy were private entrepreneurs who set about new energy business. A third of

the system installation cost was subsidized and the share of the debt which was guaranteed was 90%;

- "Support Program to Arrest Global Warming" (2001). This program aimed at supporting the activity of prevention against global warming at regional level;
- "Project for Introduction and Promotion of New Energy at the Regional Level" (2000);
- "Eco-school Infrastructure Promotion Pilot Project" (1997). The project aimed at implementing pilot model projects to demonstrate and promote environmental-friendly schools.

Notwithstanding the large budget, the programs appear to have been successful at installing progressively larger amounts of capacity even facing declining incentive levels, thereby demonstrating that buy-down programs can work over long time periods, and can lead to system cost reductions. The installed price of a residential grid-connected PV system has reportedly declined from nearly €₂₀₁₀20/Wp in 1994 to around €₂₀₁₀5/Wp in 2010 (considering that 1 €₂₀₁₀ ≈ 120 Japan Yen).

However, due to the decrease of the aids, there was a decrease in the annual installed capacity in 2007 and 2008. In order to make a trend reversal, in 2009 there was a restart of a subsidy program for residential PV systems and the start of a new program to purchase surplus PV power based upon the Act on the Promotion of the Use of Nonfossil Energy Sources and Effective Use of Fossil Energy Source Materials by Energy Suppliers. This obliged electric utilities to purchase surplus power at a double price of conventional electricity. Moreover the Government increased the target PV installed capacity by 2020 from 14 GW to 28 GW. As a result, the installed capacity more than doubled in 2009 compared to 2008. Finally, due to the earthquake of 2011 March 11, tsunami and its nuclear disaster in Fukushima, we can anticipate that Japan will encourage even more the development of renewable energies such as PV to reduce their fossil importations that increased recently.

The estimations from the METI of the subsidies for R&D, the market incentives (which comprise loans, feed-in tariffs, VAT reductions and subsidies) and the budgets for the demonstrations programs [Ikki & Tanaka, 2003; Ikki & Matsubara, 2007-2008-2010; Yamamoto & Ikki, 2011] from 1998 to 2010 are represented in Figure 36, as well as the annual installed capacity. It gives a low estimate of how much is spent to promote PV since it only represents national aids (other regional aids such as prefectures, cities, towns etc. are unknown).

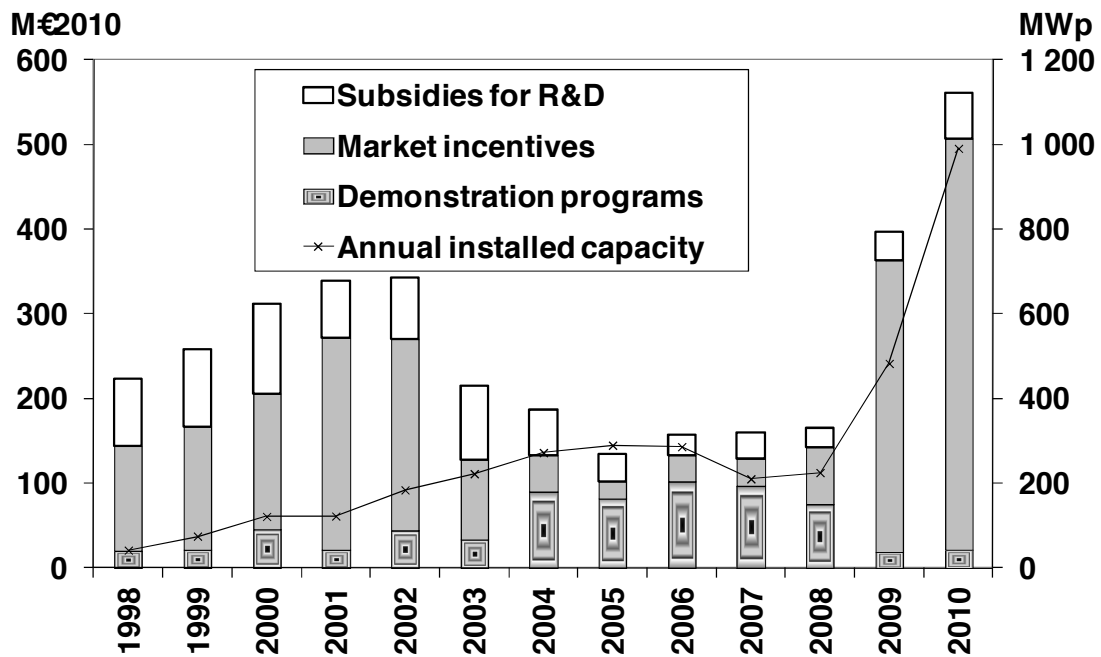


Figure 36: Annual installed capacity [MWp] and annual costs of the Japan policy to support PV [M€] from 1998 to 2010 (low estimate from METI)

What is very interesting to remark is the importance of the R&D budget in the late 90s, around 36% of the total aids to promote PV. This part is declining to around 14% in 2008 and only 9% in 2010 due to the strong increase of the market incentives, which highlights the new policy to purchase surplus PV power. This new policy can also be observed, looking at the annual installed capacity that had a significant increase in 2009 and 2010.

2.4. The US support for PV: recent and strongly dependent on the States' measures

The US support for PV began later than for the other studied countries, at the end of the 90's (State funded projects started in the 1997–1999 time frames). The difficulty is that there are federal measures and State and regional measures which are very different the ones from the others. Thus, California is clearly leading the US market with 67% of the cumulative installed capacity. The second place is for the New Jersey with only 9% and then there is Colorado with 5%.

In 1998, there were grants for PV in 12 States and loans in 15 States. Furthermore, the Department of Energy (DoE) issued a ten year plan to stimulate the deployment of one million 'solar' (PV and solar thermal) roofs with a tax credit. In 2000, in addition to the continuation of the existing projects and some new initiatives, the Utility PhotoVoltaic Group promoted competitive procurement strategies, with utilities teaming with customers to bid for the installation of around 1 MW of systems with partial financial support (about 25 %) from the DoE. In 2003, deregulation of the

electricity supply industry was enacted in twelve US States, but only seven had made provisions in the legislation to support renewable energy through system benefits credits and/or renewable energy portfolios standards. Generally utilities are unfamiliar with the connection of PV, and public awareness - outside of California - remains generally low. The years 2006 and 2007 represented a ramping-up of political discussions in preparation for the 2008 US presidential election. Energy security and climate change are bipartisan issues that have already been elevated to the top of the national political agenda. Diversification of energy sources and conservation of energy are already emerging as common themes in security and climate discussions. As pro-solar policies are implemented at State and local government levels, PV is supposed to become a bigger player in the energy mix. President Bush promised more aggressive renewable energy policy and research efforts by the Federal Government to diversify the US energy sources and mitigate climate change among other reasons. In response, the Solar America Initiative was created by the DoE to accelerate manufacturing, cost, and commercialization goals for solar energy technologies. Additionally, Federal tax credits for PV went into effect in 2006 and included a 30 % investment tax credit for commercial grid-connected systems and a 30 % tax credit for residential grid-connected PV systems with an annual cap of 2,000 \$ per system. During 2007, many States revised their renewable portfolio standards (RPS) to include solar technologies. The interest in utility-scale PV projects increased as States created more incentive programs for PV installations.

Thus, the cumulative PV installed capacity in the US reached 2,500 MW by the end of 2010. The US Federal Investment Tax Credit (ITC) legislation had a great impact on the PV market during 2008. Anxiety over the possible expiry of the ITC at the beginning of 2009 encouraged a rush by businesses and consumers to install systems using the existing credits. In October 2008 the Emergency Economic Stabilization Act of 2008 passed and extended the 30% commercial ITC until the end of 2016; it also eliminated the monetary cap for the ITC applied to residential PV installations and allowed utility companies and alternative minimum tax filers to make use of the tax credit. Thirty-two States and the District of Columbia had renewable portfolio standards in place during 2008, and five States had voluntary standards. Feed-in tariffs were offered for the first time in 2008, at the State and city government level (\$0.1/kWh in California and \$0.56/kWh in New Jersey for instance). The first city feed-in tariff was approved by Gainesville, Florida, to take effect in 2009 with \$0.32/kWh. Note that, in general, all these feed-in-tariffs are planned to last 20 years. Electricity utilities are expected to play a much larger role in deploying PV in 2009. This is because the extension of the ITC now allows the utilities to apply for the 30% tax credit. Even in the uncertain economy of early 2009, many utilities were actively planning large PV power projects to meet their generation needs.

The estimations from the DoE of the subsidies for R&D, the market incentives and the budgets for the demonstrations programs [Maycock & Bower, 2003; Maycock & Bower, 2004; Maycock & al., 2005; Pedigo & al., 2007; Poole & al., 2008; National Renewable Energy Laboratory, 2009; Bolcar & Ardani, 2011] from 1998 to 2010 are represented in Figure 37, as well as the annual installed capacity.

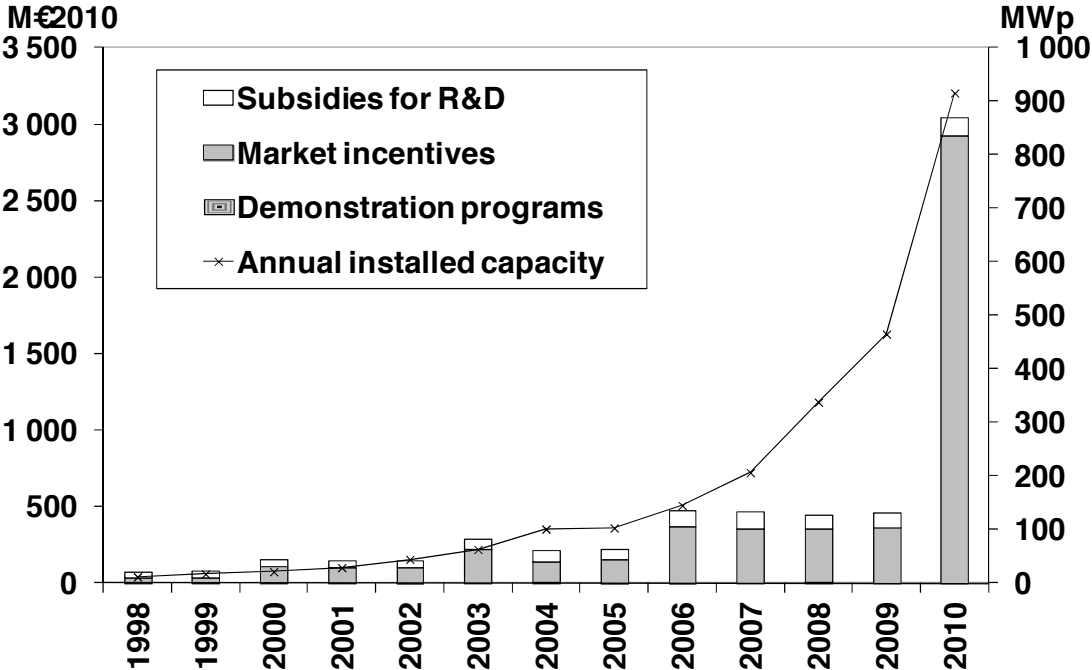


Figure 37: Annual installed capacity [MWp] and annual costs of the US policy to support PV [M€] from 1998 to 2010 (data from DoE)

We can observe the strong share of R&D in the budget allocated to promote PV. This budget represented more than fifty percent of the total aids in 1998. This budget has increased but less than the market incentives, so that percentage finally decreased to around 20% of the total aids in the period 2006-2009, and less than 5% in 2010 (in parallel, the market incentive share increased from 46% in 1998 to 95% in 2010). The demonstration programs are, in their concern, very low with less than 2% of the total amount dedicated to PV each year.

In addition, subsidies for R&D and demonstration programs are mainly supported by Federal budgets whereas market incentives are mainly supported by State and regional budgets. As a consequence, we can observe that States have played an increasingly important role in the deployment of PV (about 40% of the total amount of aids in 2001 and 2002, around 60-70% in the 2003-2007 time frames and around 80% in 2008-2009). However, the year 2010 was totally different, with a contribution of the Federal budget weighing for 88% of the total amount.

3. Comparison of the different policies to promote PV

In the previous paragraph we have seen strong differences between the studied countries (France, Germany, Spain, Japan and the US) in the way they chose to promote PV. However, the main objective is of course the same; that is to say to reach the grid parity by decreasing the cost and the price of the PV modules.

When calculating the cumulative cost of the different policies to promote PV at the end of 2010 and their sharing in terms of market incentives (investment subsidies, loans and FITs) and technologies incentives (R&D and demonstration programs), the differences are highlighted (see Figure 38 and Figure 39). Thus, the average cost spent per Wp until 2010¹⁰ (see Table 12) was calculated at around €2.6 for France, €1.1 for Germany, €1.1 for Spain, €1.0 for Japan and €2.5 for the US. The best scheme until today seems to be the Japanese one. With their large demonstration programs (more than 25% of the total incentives at the end of 2010 – see Figure 39), they were able to choose the size, the location and the kind of installations to subsidize as well as the installed capacity per year. In parallel, the part dedicated to R&D was significant. Germany, which also has a low average cost in 2010, led a totally different policy to support PV, with a strong effort on feed-in tariffs. The consequence is the highest cumulative installed capacity in the world, but we can be dubitative about the interest to install such a large capacity when the cost is still very high looking at the grid prices (as it will be shown later, cf. Figure 43 p.112). If the average cost is not too high today (see Figure 39) due to the important capacity installed every year, it will be different in the future and will heavily impact the electricity mix price. Indeed, when the annual installed capacities are of the same order of magnitude than the cumulative ones, the cumulative effect of the feed-in tariffs is not too visible; on the contrary, when the annual installed capacities are small compared to the cumulative ones, the cumulative effect of the feed-in tariffs is weighing more and more (see Figure 40, what can be observed for Spain in 2009). With the same value of the average cost spent per Wp until 2010 (€1.1), Spain is far from being a model. Indeed, the very attractive feed-in tariffs of 2007-2008 which led to a spectacular boom in term of installed capacity (3,345 MWp cumulative installed PV capacity at the end of 2008) will imply high public expenses during 25 years. Therefore, this low average cost will be increasing very quickly: it was 0.6 in 2008 and is already around €1.1/Wp in 2010 and it will continue to grow. As for the US, they began to support PV comparatively late. The result is a cumulative installed capacity 30% lower than the Japan's one. At the present time, the amounts dedicated to R&D are significant, but they are decreasing in favour of market incentives which

¹⁰Cumulative costs divided by the cumulative installed capacity

comprise feed-in tariffs. So, as for Germany and Spain, the average cost spent per Wp is intended to increase. Finally, the French policy appears to be the least efficient one with the highest average cost in 2010. The main spending concerns the investment subsidies for nearly 70%. However as for the other European countries feed-in tariffs are going to weigh more and more in the future.

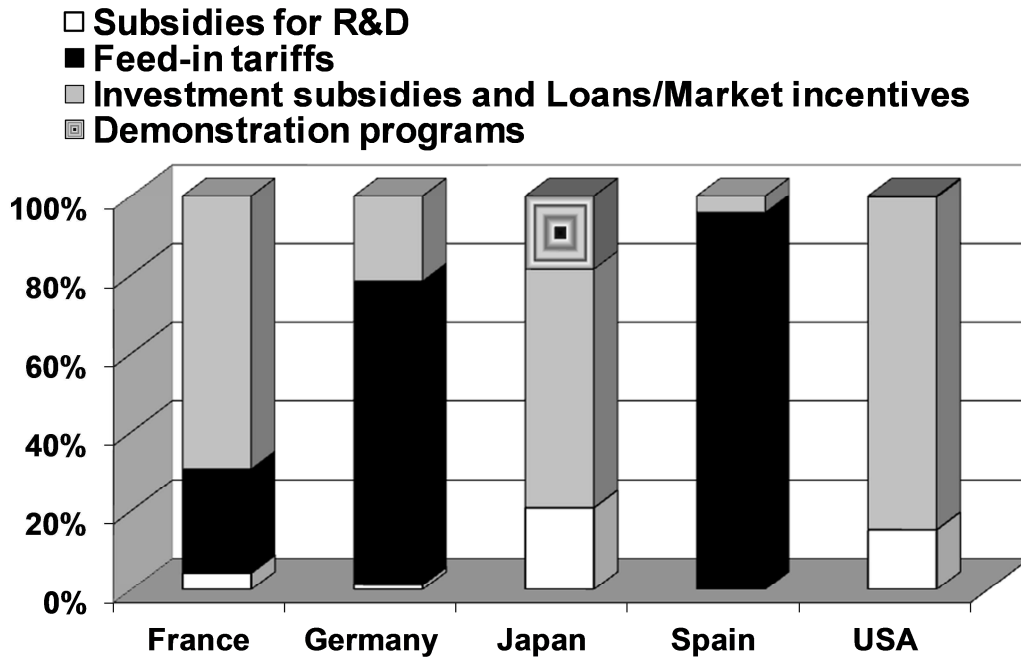


Figure 38: Sharing out of the cumulative cost at the end of 2010 between demonstration program costs, feed-in tariffs, market incentives (other than FIT), and subsidies for R&D in France, Germany, Japan, Spain and the USA (R&D is unknown for Spain)

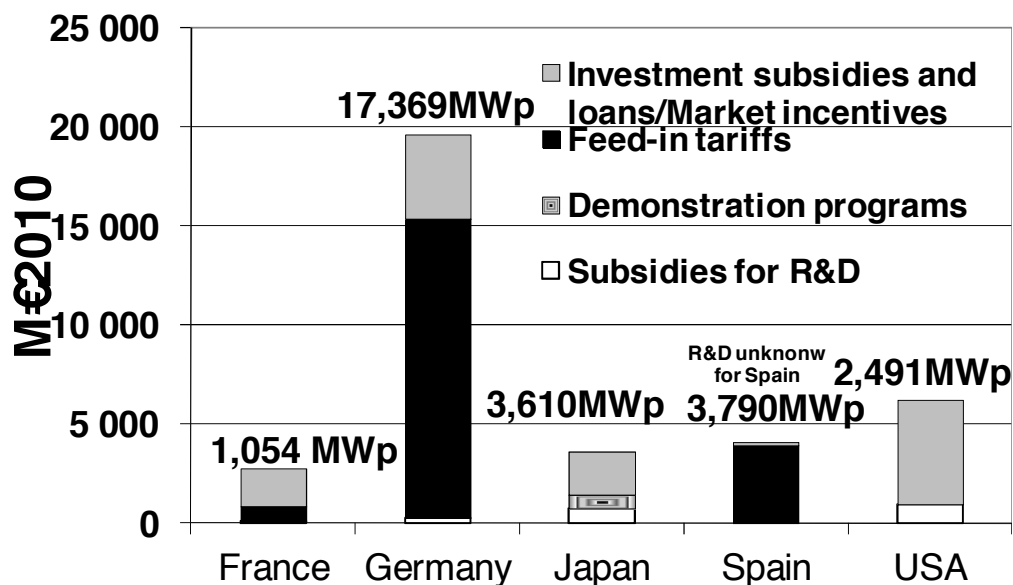


Figure 39: Cumulative cost of the policies to promote PV at the end of 2010 in France, Germany, Japan, Spain and the USA

Table 12: Average cost [€/Wp] spent to promote PV at the end of 2010 in each country (i.e. cumulative cost divided by the cumulative installed capacity)

France	Germany	Japan	Spain	USA
2.6	1.1	1.0	1.1	2.5

Another interesting result is the annual costs of PV incentive in €/Wp (for each year, we are considering the public support during the year studied divided by the annual installed capacity the same year). On Figure 40 we can observe the evolution of this value from 1990 until 2010.

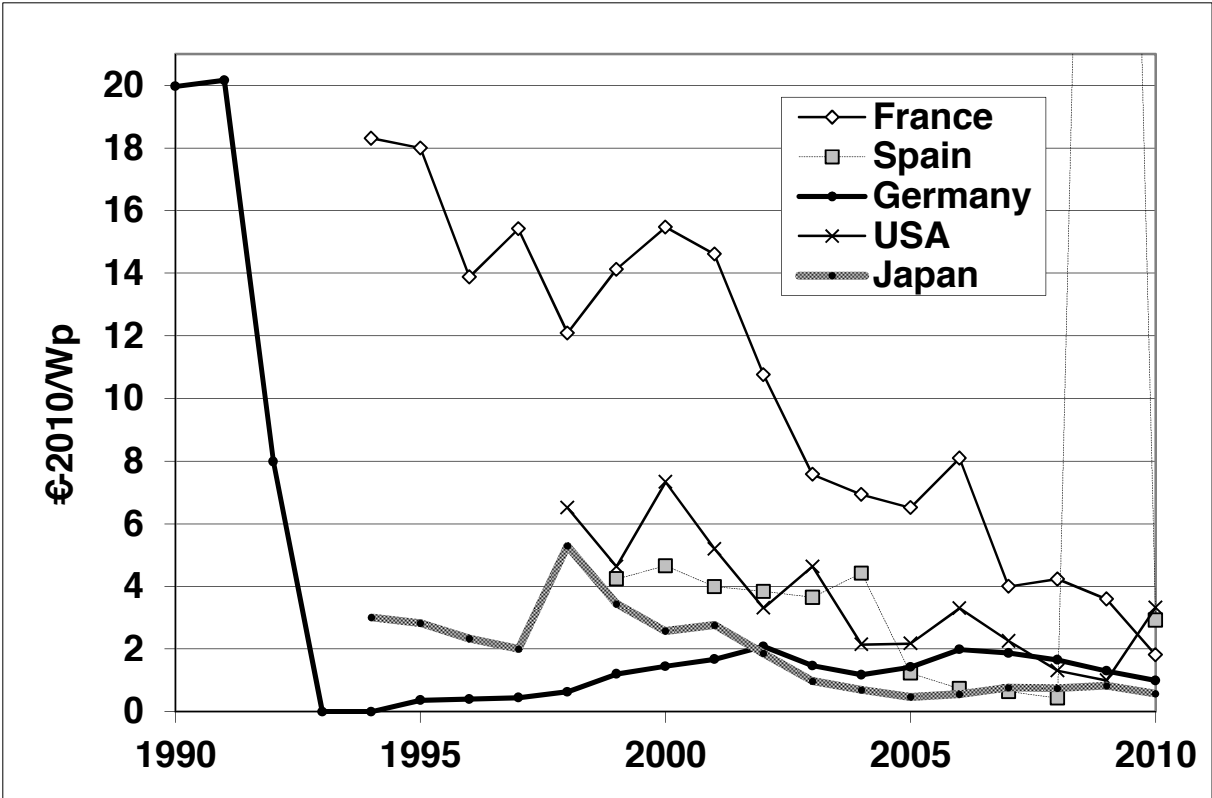


Figure 40: Annual costs of PV incentives in €/Wp in France, Germany, Japan, Spain and the USA from 1990 until 2010

As explained in the introduction, comparing the efficiency of public policies for promoting renewable energy is a stiff challenge due to the lack of a common definition for all the ways of subsidies, and to the variability of the data.

Although it presents major flaws, the annually evaluated cost provides an indicator of the side-effects of the different energy policies. Indeed, even if only capturing an instantaneous state of the economic situation, this criterion is highly sensitive to the irregularity effects in the capacity growth. Thus the balance between the subsidies and their immediate consequence can be checked. On the whole, the overall trend is to decrease. Specifically, the case of Spain is very enlightening since the

effect of the too high feed-in tariffs in 2007-2008 and their strong decrease in 2009 has created a discontinuity in the evolution with a boom in 2009 of €67/Wp (the previous value was €0.44/Wp in 2008). Indeed, in 2009 the amount of the feed-in tariffs due to the installed capacity of 2007 was doubled whereas the annual installed capacity was very low because of the new feed-in tariffs. Hence the absurdly high €/Wp value for Spain in 2009 is a good indicator of the saturation effect of the installation program which could be, for instance, due to a speculative reflex. If this price is not realistic, it represents an accident that should goad a politic response. Moreover, when integrated over years this phenomenon should be toned-down by the market adaptation.

Concerning the observed decreasing value of the other countries, it can be explained by the fact that the technology cost is decreasing whereas the installed capacity continuously increases. This trend has not to be abusively extrapolated in the next years since the recent revisions of the feed-in tariffs could lead to a situation similar to the Spanish one with a slowing down of the annual installed capacity. An increase of the value for the USA can already be observed in 2010 (the value was multiplied by three in one year).

Similar trends are observed on Figure 41, in which we assessed the evolution of the installed Wp cost from the cumulative public support until this year against the cumulative installed capacity. A discount rate of 8% was used. We can observe the same effects as above mentioned: the average Wp cost increases when the installation rhythm is slowed down, whereas the already installed capacity generates a significant cost.

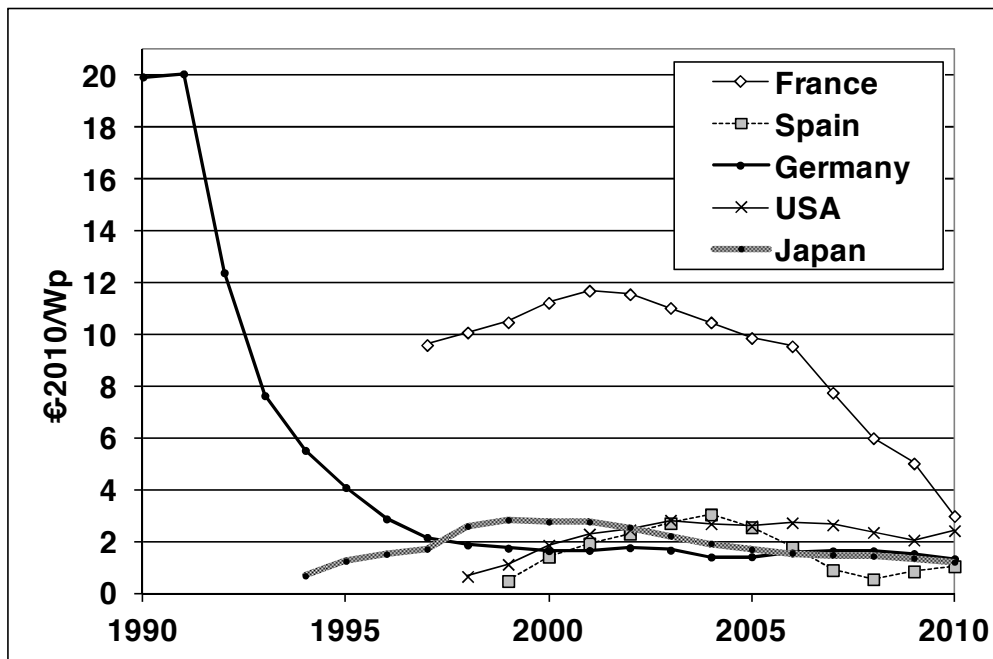


Figure 41: Assessment of the installed Wp cost from the cumulative support in France, Germany, Japan, Spain and the USA from 1990 until 2010 (discount rate 8%)

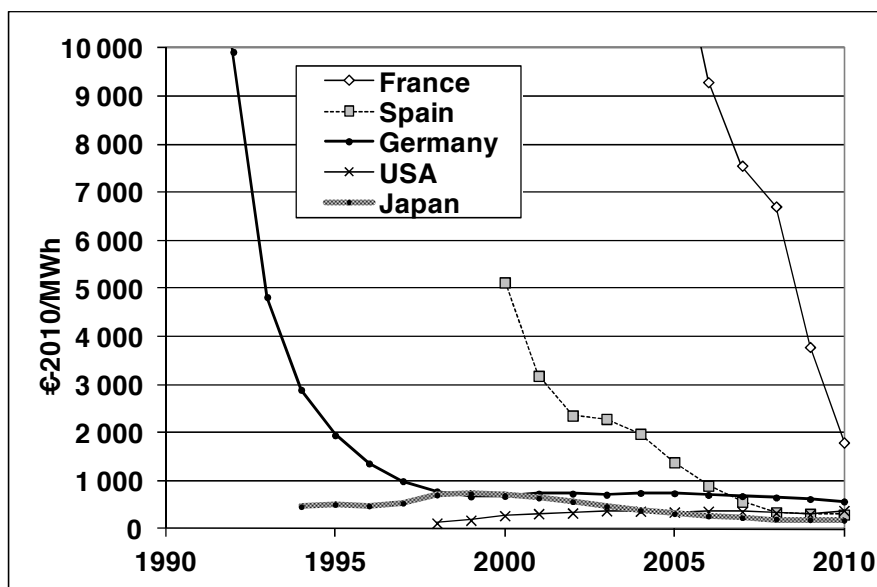


Figure 42: Assessment of the produced MWh cost from the cumulative support in France, Germany, Japan, Spain and the USA from 1990 until 2010 (discount rate 8%)

Finally, we propose to assess the evolution of the average PV MWh cost on the considered period. This is what is done in Figure 42 from the cumulative public support data when using a discount rate of 8%. Results show that high initial costs can be rather quickly balanced by the amount of produced energy. This is quite spectacular in the case of Germany which seems to have reached a stabilization phase. The same kind of curve can be observed for Spain – respectively for France, with a delay of 7 years- respectively 15 years. For Japan and the USA the spectacular high costs in the beginnings are not observed because of a higher cumulative installed capacity than in France, Germany and Spain; these two countries began with an increase of the PV cost and a decrease since 1999 for Japan and 2003 for the USA (this is mainly due the speed of the increase of cumulative capacity, very low at first since these countries chose a techno-push policy with a high amount of R&D subsidies, and then very fast). However, the achieved MWh cost remains quite high (see Table 13) compared to “conventional” power plants [IEA 2010a]. Further cost decrease could be facilitated through the use of the other lever: investing in R&D. Japan again demonstrates a success story when considering this indicator.

Table 13: Average PV MWh cost at the end of 2010 in each country (discount rate of 8%)

France	Germany	Japan	Spain	USA
1798	572	179	300	384

The evolutions of these five countries' incentives to promote PV show the importance to have a well-planned policy and not a haphazard policy. The States must control the installed capacity which has not to be too high but also not too low in comparison with the previous years (in particular to smooth the consequences in terms of local employment). They must also control the location of the installations they want to subsidize (repartition on the territory, repartition in terms of kind of installation – roof integrated or not for instance, distance from the existing grid, etc.) and do not forget to couple an actual R&D policy to the market incentive implementation. Indeed, as above mentioned, technology-push policies should prevail during the first innovation phases, while demand-pull measures are predominant at the end when the technology becomes more mature. To assess the match between the implemented policy and the technology maturity, the R&D support dynamics was therefore assessed in comparison with the gap to grid parity. The latest was defined as the ratio between the PV MWh cost (depending on the system price for the considered year) and the household electricity price. The assessment is represented on Figure 43. The gap to the grid parity is very dependent on the studied country (solar potential, existing electricity mix) and thus cannot be used to evaluate the maturity of the technology as a whole; however, it is a good thing to appreciate the potential to penetrate the electricity market, and so the need of public support and the level of R&D that has to be maintained. The discontinuity of the French policy is pointed out: R&D share is really low despite the fact that in France grid parity is still a long way coming. As for Germany, after having put some significant effort in the earlier development phases, the R&D support is now quite small. This is explained by the fact that grid parity is quite close, partly due to the recent increase of the electricity price. Finally Japan maintained steady effort on R&D, also probably because grid parity is not achieved yet. Germany and Japan, despite close values of gap to parity do not seem to appreciate the maturity of PV equally. Note that another driver for deciding the level of R&D is its connection to the industrial landscape.

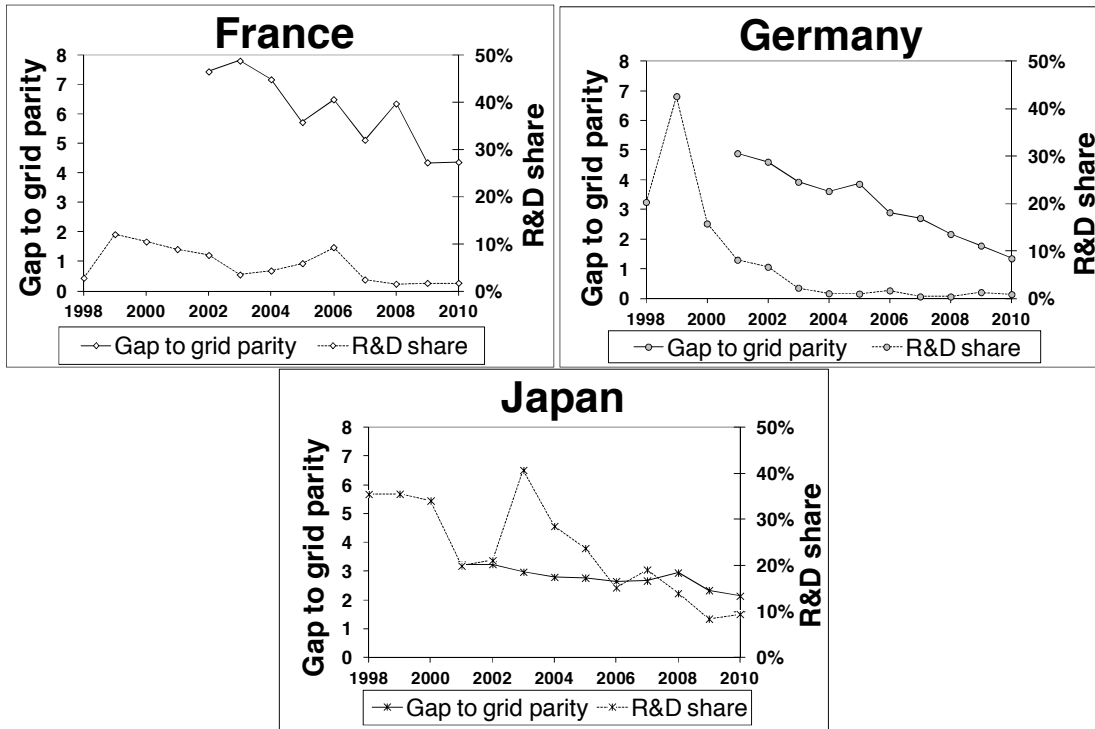


Figure 43: Gap to grid parity (€/MWh / €/MWh) and R&D share in the total public support for France, Germany and Japan

Finally, it is interesting to look at the PV system selling prices in order to ensure the efficiency of the PV policies. The indicative installed system prices in 2010 are provided by the IEA [IEA, 2011] for systems lower than 10 kW and upper than 10 kW. The intervals of current values are represented in Figure 44.

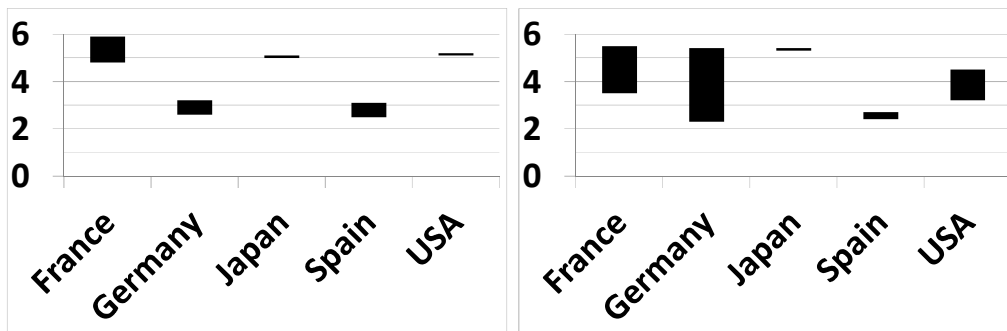


Figure 44: Indicative installed system prices in 2010 [€/2010/W] for systems < 10kW (on the left) and > 10kW (on the right), from [IEA, 2011]

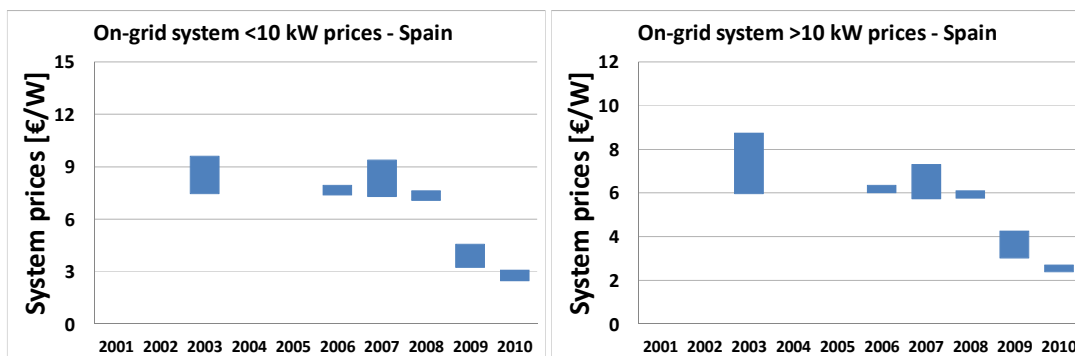


Figure 45: Evolution of the system prices in Spain over the last decade, from [IEA 1998-2011]

We can observe strong differences between the five studied countries. For small systems (< 10 kW), Germany and Spain provide systems twice as cheap as in other countries, French systems being the more expensive. For the bigger systems (> 10 kW), ranges are wider. Spanish systems are still cheaper whereas French systems are still more expensive. This is another bad point for France whose high expenses are not related to significant decrease of the PV system prices. This is mainly due to the 50% tax abatement with an upper limit of 16,000 € for private individuals (2006 - 2009) which did not incite to decrease the price even if the cost did. Besides, this tax was reassessed and decreased to 25% on the 29th of September 2010 and to 22% in 2011. In the particular case of Spain, the decrease of the prices of the systems was only observed after the new policy implementation in 2009-2010 (installed capacity ceilings, lowered feed-in tariffs – see Figure 45). In 2008, the prices were as high as in France; this is probably the high demand for installing new systems because of the profitable feed-in tariffs which has kept prices artificially high. This is clearly a speculative effect. However, the installation cost has benefited from the increasing installed capacities (decrease in the installation cost and then in the system prices). The differences between Germany, Japan and the USA are not so big, and they probably depend on the cost of the balance of systems, the lower prices being in the countries that installed larger capacities each year.

4. Conclusion of chapter three: a well-planned rather than an haphazard policy

The aim of this chapter was to quantify how much money has been spent to boost PV in France, Germany, Spain, Japan and the US in order to analyze the different policies. After having described the mechanisms of public support in relation with the cost reduction of PV systems, we have evaluated the annual cost of public support for PV from an extensive policy review. This cost is

divided into different measure categories: investment subsidies and loans and market incentives, feed-in tariffs and subsidies for R&D, and was considered against installed capacities.

No country can be said to have a perfect policy since each one is a particular case (different electricity mixes, different energy dependences, different electricity prices, different involvement of the Governments, etc.).

To our point of view, a recommended policy would be starting, as Japan did, with a focus on demonstration programs which enable to control the PV development (which systems, where, how many) in the first phase when the technology is not mature and strong R&D support in order to improve the technologies. In a second phase, when the technology is more mature, feed-in tariffs and other demand-pull policies (tax abatements, etc.) are relevant to boost the penetration in the market. In this phase, a sufficient R&D level should be proceeded to maintain an adequate equilibrium among the public expenses. Such trends have been recently observed, with a spread of feed-in tariffs to a number of countries (e.g. China [Huo & Zang, 2012], Australia [Avril & *al.*, 2012b]) as well as the increase of the R&D since 2010 in the considered countries.

Moreover, when using feed-in tariffs, appropriately differentiated ones could also be efficient to reach this balanced PV development, as pointed out by [Lesser & Su, 2008].

Another important thing is to have a well-controlled progression of the installed capacity. The counterexample of Spain shows the problem of a quick development, which does not only lead to higher prices due to the sudden high demand but could also involve a later rupture which could have a strong impact on the local employment.

Besides, close attention must be paid to the feed-in tariffs. Indeed, if their creation clearly boosted the market, the long term impacts are far from being insignificant. In the case of France, they have been prospectively evaluated around 1 billion per year in 2020. This would be probably higher in countries with a larger installed capacity like Germany.

Finally, we have to keep in mind that cost reductions and price reductions are not necessarily correlated. In other words, we have to be wary of mask effects of some policies. The French case is a good illustration of that problem, since it appears that the PV system price is higher than in other countries due to the high ceiling of the tax abatement.

Concerning the R&D incentives, their impacts on the installed capacity are not obvious with this study. In our opinion, it has to be studied in more details.

To pursue this study, it would be very interesting to look at the next years' events in order to see how the market will react to the new European feed-in tariff measures of 2010 and afterwards.

Indeed, the decrease of the feed-in tariffs will certainly cause a slowdown in the annual number of installations; coupled to the increase of the global photovoltaic production capacity, it will impact a lot this industrial sector. A good illustration is the situation in Germany; indeed, *“after Solon, Solarhybrid, and Solar Milenium, a fourth German specialist in solar announced April 3, 2012 filing for bankruptcy”* [Le Figaro Economie, 2012].

It would also be interesting to enlarge this study to other significant countries like China and Taiwan which are leading the PV system production market, and also implement supporting policies domestically.

Conclusions and perspectives

Summary of the dissertation

In the first chapter, we decided to focus on the place of the photovoltaic energy in the global mix. Our concerns are that it is of high importance to incurve our energy mix in a sustainable way, without polluting emissions, but also giving access to energy to all the people at affordable prices. This implies a reduction of the use of fossil energies. This can be done by an increase of the efficiency, but also by a higher use of decarbonized electricity. Thus, renewable energy must play an important role in the future years, and especially the solar photovoltaic energy which has a high potential despite its drawbacks of intermittency and still high prices.

Then, in the second chapter, we focused on proposing solutions to the intermittency limitation. To meet this target, we developed a techno-economic optimization methodology implemented through a particle swarm optimization code devoted to design a system composed of an electricity consumer, photovoltaic panels and storage devices. The outcome of the model is the total levelized cost of the whole system as the central criterion, but the methodology is intrinsically multiobjective. This model was used to examine the specific situation of insular remote areas where photovoltaic power is of great interest and to optimally design photovoltaic systems in such contexts. Regarding the results, we can say that the system is expensive, but mainly due to the high cost of storage devices. In the medium term, due to the cost reduction of PV panels, the need of storage devices would be then reduced and the whole system more affordable. Moreover, considering limited areas, it is worth using high efficiency cells; indeed despite their higher cost, they can provide the cheapest system thanks to their high efficiency and the lower need of storage devices.

Finally, we evaluated the efficiency of the public support for photovoltaics in five representative countries. Our conclusions are that the feed-in tariffs are very efficient to create a market but that they are very expensive and need to be used very carefully and not too early (demonstration project should be preferred at first). Another important concern is to have a well-controlled progression of the installed capacity, in terms of installed power and localization. Furthermore, we warn about mask effects, especially when using tax abatements.

Importance of the multidisciplinary treatment of energy issues

In these works, we put into relief the necessity to consider energy issues through the prism of technical basis. Indeed, solutions that cannot be efficient should not be implemented in the system.

However, a solely technical treatment of energy challenges is obviously insufficient, since energy is core point for the economy, for the citizen and so for the politician. Consequently, in order to carry out a performing analysis of the entire energy problematic, different disciplines are required (applied mathematics, physical sciences, economics, geopolitics). Note that such a combined approach needs to remain anchored on concrete data close to the reality of the technical devices and keeping in mind the financial feasibility of the proposed solutions, when designing a new energy landscape and thus a new societal model.

Perspectives

This work focused on two main orientations.

Concerning the development of the MOMuS model in order to design and optimize a system with photovoltaic panels and storage, we think that there are many further developments to do. Firstly, it would be interesting to test it on other real cases and to further develop it with other storage devices. Another way of improvement concerns the consideration of the geographical repartition of the utilities (issues of grid design for instance). It would be worth analyzing existing software in order to decide if it is preferable to couple it to MOMuS or to develop MOMuS in order to add this functionality.

Concerning the link between public policies and energy technologies, we must pursue our monitoring of any changes, in order to benefit from the mistakes of the past in a very dynamic context, and thinking of the long-term. For instance, the measures that will be taken to encourage the self-consumption of generated solar energy should be screened very carefully.

With this thesis, I stepped back on my works with organizing it, putting in perspective with the literature and highlighting two-level skills: i/a holistic view of energy policy, mixing technical constraints in a geopolitical framework; ii/being particularly accurate in specific aspects related to renewable technologies and their potential in the energetic mix.

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Appendix

Appendix 1: The EDELVEISS project

These studies have been carried out in the CEA (*Commissariat à l'énergie atomique et aux énergies alternatives* - French Alternative Energies and Atomic Energy Commission) within the context of the EDELVEISS project (*Évaluation avant Démonstrations Expérimentales en Lignes de la Valorisation de la production Électrique Intermittente par les Systèmes de Stockage* – Evaluation before experimental testing of the valorisation of the intermittent electrical production thanks to energy storage devices) from 2007 until 2009.

Members of the consortium

This project gathered the skills of different teams: i) I-tésé (*Institut de technico-économie des systèmes énergétiques* - Institute for techno-economics of energy systems) for the coordination of the project and for the techno-economic approach, ii) the LGLS (*Laboratoire de génie logiciel et simulation* – Laboratory of software engineering and simulation) for its skills in simulation and optimization, iii) the INES (*Institut National de l'Energie Solaire* – National institute for solar energy) for its knowledge in PV technologies and in technologies of batteries, iv) the DTBH (*Département des technologies biomasse et hydrogène* - Hydrogen and Biomass Department) for its skills in the hydrogen chain, v) and finally the ARER (*Agence régionale de l'énergie de la Réunion* – Regional agency for energy in *La Réunion* island) for the *in situ* data of the studied system (meteorological data and electricity consumption).

Scope of the EDELVEISS project

The main aim of the EDELVEISS project was to check if the promising energy storage devices (innovative batteries, hydrogen-based storage technologies...) currently developed through the CEA R&D programs could match the future energy market in terms of cost, adaptation, performance standards, etc. To meet this point, even if all the possible applications should be prospected, the first step consisted in focusing on stationary applications. Due to the weakness of the electric network and the high cost of their electricity production, the principal market of a large scale stationary energy storage system corresponds to the islands situation. Moreover, considering its high solar

potential and the political will to meet a 100% electrical autonomy in the French overseas departments for 2025 [PRERURE, 2005], the case of the French department of *La Réunion* island is a good candidate to be studied. That is why, in the second part of this chapter, a special focus on the situation of this island is presented analyzing the optimal design of the coupling of PV and storage devices. The model that has been developed to perform the simulations is first presented.

Appendix 2: The learning curve

There are different learning curve models. The original model was developed by T. P. Wright in 1936 and is referred to as the Cumulative Average Model or Wright's Model [Wright, 1936].

Wright's Cumulative Average Model

In Wright's Model, the learning curve function is defined as follows:

$$Y = aX^b$$

where:

Y = the cumulative average cost per unit.

X = the cumulative number of units produced.

a = cost required to produce the first unit.

b = log of the learning rate/log of 2.

Appendix 3: Scientific production

International journals with referees

- J1** S. Avril, C. Mansilla, M. Busson, T. Lemaire, "Photovoltaic energy policy: financial estimation and performance comparison of the public support in five representative countries", *Energy Policy*, **2012** 51, 244-258.
- J2** C. Mansilla, S. Avril, J. Imbach, A. Le Duigou "CO₂-free hydrogen as a substitute to fossil fuels: What are the targets? Prospective assessment of the hydrogen market attractiveness", *International Journal of Hydrogen Energy*, **2012**, 37(12), 9451-9458
- J3** S. Avril, C. Mansilla, T. Lemaire, "Solar energy support in the Asia-Pacific region ", *Progress in Photovoltaics: Research and Applications*, **2012**, 20(6) 785-800.
- J4** S. Avril, G. Arnaud, H. Colin, F. Montignac, C. Mansilla, M. Vinard, "Cost and surface optimization of a remote photovoltaic system for two kinds of panels' technologies", *Journal of Power Sources*, **2011**, 196(19) 8166-8169.
- J5** C Mansilla, S. Dautremont, B. Shoai Tehrani, G. Cotin, S. Avril; E. Burkhalter, " Reducing the hydrogen production cost by operating alkaline electrolysis as a discontinuous process in the French market context", *International Journal of Hydrogen Energy*, **2011**, 36(11) 6407-6413.
- J6** S. Avril, G. Arnaud, A. Florentin, M. Vinard, "Multi-objective optimization of batteries and hydrogen storage technologies for remote photovoltaic systems", *Energy*, **2010**, 35(12) 5300-5308.
- J7** T. Bärecke, C. Mansilla, S. Avril, B. Bouchon-Meunier, M. Detyniecki, F. Werkoff, "Fuzzy sets for assessing the profitability of hydrogen production by the Sulphur-Iodine thermochemical cycle", *International Journal of Energy, Environment and Economics*, **2010**, 19(1-2) 119-132.

National and International conferences

- C1** S. Avril, C. Mansilla, P. Da Costa & J.-C. Bocquet, " Photovoltaic energy: a key player towards a sustainable energy mix ", 13th World Renewable Energy Congress/Network (WREC VIII), University of Kingston, London, UK, 3-8 August **2014**, *accepted*.
- C2** S. Avril, G. Arnaud, J. Szustakowski, C. Mansilla, " Optimizing the storage contribution to the reduction of grid connection needs in the case of wind power production", 7th International Renewable Energy and Storage (IRES 2012), Berlin, 12-14 November **2012**.
- C3** S. Avril, C. Mansilla, "Background, financial estimation and performance comparison of different public support policies for photovoltaic deployment in North America, Europe and Asian countries", 26th European Photovoltaic Solar Energy Conference (PVSEC 2011), Hamburg, 5-9 September **2011**.
- C4** S. Avril, G. Arnaud, H. Colin, F. Montignac, C. Mansilla, M. Vinard, "Optimization of a remote photovoltaic system coupled to storage in an island context", 5th International Renewable Energy and Storage (IRES 2010), Berlin, 22-25 November **2010**.
- C5** F.Montignac, S. Avril, R. Batisse, S. Lim, B. Weinberger, S. Melscoet, J.-Ch. Hoguet, "The use of hydrogen pipelines for wind energy storage: case studies for a techno-economical assessment", 5th International Renewable Energy and Storage (IRES 2010), Berlin, 22-25 November **2010**.
- C6** S. Avril, participation in the Roundtable "Role and regulation of Storage in electricity networks", Workshop on Electricity Storage in Paris-Supelec, Gif-sur-Yvette, 10 May **2010**.

- C7** S. Avril, C. Mansilla, F. Thais, "*Efficacité et solaire photovoltaïque* ", Journée de l'I-tésé, 3 juin **2010**
- C8** S. Avril, "*Le stockage d'énergie : enjeu majeur du déploiement des énergies renouvelables*", Journée de l'I-tésé, 3 juin **2009**.
- C9** C. Mansilla, S. Avril, R. Rivera-Tinoco, "*What target cost for the advanced processes for massive hydrogen production?*" 17th World Hydrogen Energy Conference (WHEC 2008), Brisbane, June **2008**.
- C10** S. Avril, JM Agator, "*Toward a French Hydrogen Energy Roadmap: the HyFrance project* ", First Budapest International Hydrogen Energy Forum, Invited Conference, Budapest, October **2006**.
- C11** F. Werkoff, S. Avril, C. Mansilla, "*Processes of hydrogen production coupled with nuclear reactors: economic perspectives* ", Autumn-Seminar of Swiss Nuclear Society, Zurich, Septembers **2006**.
- C12** J.M. Agator, S. Avril, "*Toward a French Hydrogen Energy Roadmap: the HyFrance project* ", 16th World Hydrogen Energy Conference (WHEC 2006), Lyon, June **2006**.
- C13** T. Baerecke, C. Mansilla, S. Avril, B. Bouchon-Meunier, M. Detyniecki, F. Werkoff, "*On the use of genetic algorithms and fuzzy logic for the assessment of the cost of hydrogen to be produced by advanced processes* ", 2006 Fuel Cell Seminar, Hawaii, November **2006**.
- C14** F. Werkoff, S. Avril, C. Mansilla, J. Sigurvinsson, "*Processes of hydrogen production coupled with nuclear reactors: economic perspectives* ", European Nuclear Conference (ENC 2005), Versailles, December **2005**.

Other (Expertise/Vulgarization)

- O1** S. Avril, P. Odru, "*Optimisation des énergies intermittentes par l'utilisation d'hydrogène* ", in « Hydrogène : Carburant de l'après-pétrole ? », Ed. P. Lucchèse et E. Freund, Technip, Paris **2012**, 147-15.
- O2** S. Avril, « Quel impact sur les ressources lithium du développement des véhicules électriques ? », communication invitée à la Chair Armand Peugeot sur l'électromobilité, La Défense 25 juin **2012**
- O3** S. Avril, A. Berwald & F. Legée, "*Impact des tarifs de rachat des énergies renouvelables sur la facture d'électricité : une comparaison France-Allemagne*, La lettre de l'I-tésé, n°17, **2012**
- O4** Membre de l'Editorial Board de International Journal of Energy Optimization and Engineering (IJEEO) (**2011-2012**)
- O5** Request for expertise for EPFL (**2011**) and ANR (**2012**)
- O6** S. Avril, F. Legée, "*Facture d'électricité : de nouvelles mesures sur les taxes en 2011*, La lettre de l'I-tésé, n°12, **2011**
- O7** S. Avril « *l'enjeu énergétique du lithium, 3 questions à Sophie Avril* », Les Défis du CEA, n°159, **2011**, p.18.
- O8** S. Avril, C. Mansilla, F. Thais, "*Efficacité et solaire photovoltaïque*, La lettre de l'I-tésé, n°10, **2010**
- O9** S. Avril, "*Le triangle du Lithium : vers un nouvel Eldorado*", La chaîne énergie (L'Expansion) <http://energie.lexpansion.com/prospective/>, article en ligne le 2 février **2010**
- O10** Interview par « le quotidien de l'actu »- n°2942, Le lithium, « moteur » des voitures électriques 29 août **2009**