THÈSE DE DOCTORAT

de l'Université de recherche Paris Sciences et Lettres
PSL Research University

Préparée à l'Université Paris-Dauphine

Public policies for the development of solar photovoltaic energy and the impacts on dynamics of technology systems and markets.

École Doctorale de Dauphine — ED 543

Spécialité **Sciences économiques**

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à Aline (아린)

Remerciements

Ce projet de thèse a été réalisé à l'Institut de Technico-Économie des Systèmes Énergétiques (I-tésé) du Commissariat à l'Énergie Atomique et aux Énergies Alternatives (CEA) sous l'encadrement académique de l'Université Paris-Dauphine. Cette thèse n'aurait pas pu se réaliser sans le soutien d'un grand nombre de personnes.

En premier lieu, j'exprime ma profonde gratitude à mon directeur de thèse, M. Patrice Geoffron, pour m'avoir fait découvrir ce sujet de thèse au CEA et pour avoir accepté d'être mon directeur de thèse. Je le remercie pour ses conseils académiques sur le secteur de l'économie de l'énergie et pour ses encouragements durant toutes ces dernières années.

J'adresse de chaleureux remerciements à mon encadrante, M$^{\text{me}}$ Nathalie Popiolek, pour tous ses efforts préalables pour défendre et financer ce projet de thèse et pour m'avoir fait confiance pour mener à bien les travaux. Son attention de tous les instants, ses conseils avisés, et ses orientations scientifiques m'ont conduite à la réussite de cette thèse. Son énergie et sa rigueur ont été des éléments moteurs pour moi et j'ai beaucoup appris en travaillant avec elle.

Je remercie également l'ensemble du jury pour l'intérêt qu'ils ont porté à mon travail et pour le temps qu'ils ont consacré à l'examiner. Je voudrais remercier M. Patrick Criqui et M. Yannick Perez qui ont accepté d'être les rapporteurs, M. Jan Keppler, M. Jean-Pierre Joly et M. Jean-Guy Devezeaux de Lavergne, qui ont accepté d'être les examinateurs.

Ensuite, je souhaite exprimer tous mes remerciements à M. Michel Cruciani pour ses conseils éclairés et sa relecture attentive de mes articles de conférences et articles scientifiques m'ayant permis d'améliorer la qualité de mon travail.

Ma gratitude va également à M. Reinhard Haas, Professeur et Directeur de l'Institut des Systèmes Énergétiques et des Entraînements Électriques de l'Université Technique de Vienne pour les échanges enrichissants que nous avons eu lors des conférences, pour m'avoir fourni d'intéressants articles scientifiques et pour ses encouragements. Je remercie plus généralement tous les experts du domaine du photovoltaïque et de l'économie de l'énergie que j'ai rencontrés lors de mes conférences (IEPEC, EU PVSEC, EEM, IAEE). Écouter leurs opinions et discuter avec eux autour de ces sujets a été très instructif et m'a apporté des éléments essentiels pour la construction de cette thèse. J'ajoute à ces remerciements mes anciens collègues de Linde qui m'ont informé de certains aspects industriels et pour leur soutien.

J'exprime aussi mes remerciements aux collègues du CEA. Merci à nouveau à Jean-Guy pour m'avoir accueillie au sein de son équipe dans de bonnes conditions de travail et pour la confiance qu'il m'accorde pour la suite de mes activités professionnelles. Je remercie encore vivement M. Jean-Pierre Joly ainsi que M. Philippe Malbranche de l'INES pour leurs retours très utiles en tant qu'expert du secteur PV et leur point de vue scientifique et industriel sur le sujet. Merci également à M$^{\text{me}}$ Nicole Mermilliod qui a beaucoup travaillé pour trouver le financement de cette thèse.

Je désire bien entendu remercier toute l'équipe de l'I-tésé pour sa sympathie, son professionnalisme et son soutien et au sein de laquelle j'ai un grand plaisir à travailler. Je dis merci à chacun d'entre eux: Patricia, Françoise, Christine, Anne, Elisabeth, Sophie G., Séverine, Thierry, Gille, Michel, Fréderic, Alain, ainsi qu'aux anciens collègues, Sophie A., Yves et Didier. Je souhaite remercier spécialement Patricia pour son attention chaleureuse et son aide efficace durant toutes ces années ainsi que Yves et Fréderic, nos ancien et actuel correspondants informatiques pour leur aide précieuse sur les sujets informatiques.

Aussi, je tiens à remercier les doctorants de l'I-tésé: Camille, Antoine, Linh, Martin et Robin pour les bons moments passés ensemble pendant ces dernières années sans oublier nos anciens doctorants Anton et surtout Bianka pour ses bons conseils sur la réalisation de la thèse. Je n'oublie évidemment pas tous les doctorants anciens et actuels du CGEMP et du CEEM, Antoine, Marie, Thao, Noriko, Kenza, Yuanjing et Manuel pour qui j'ai une pensée très amicale.

Pour ceux que j'aurais éventuellement oublié de citer, soyez sûr que vous ne serez pas oubliés dans mon cœur.

Pour conclure, je souhaite remercier toute ma famille ainsi que mes amis pour leur soutien et leurs encouragements pendant la période de thèse. Je souhaite surtout exprimer un grand merci à mon mari, Yann, qui m'a soutenue tout au long de cette thèse avec beaucoup d'amour et de patience. De plus, le partage de son intérêt pour le secteur de l'électricité et de l'énergie en général m'a beaucoup motivée. Enfin, j'ai une pensée pour ma petite fille, Aline, qui a déjà présenté avec sa maman dans deux conférences internationales à Lisbonne et Antalya! Je lui dis merci d'avoir été aussi gentille lors des derniers mois de travail et je lui dédie cette thèse.

Abstract

Over the past decades, climate change has been a subject of serious international negotiations. Solar photovoltaic (PV) energy has caught the eyes of many governments as one of the front-runner technologies for the low carbon energy transition in the global community. Solar PV systems have experienced strong market growth over the last decade supported by favorable political reactions in the energy transition context. However, despite these favorable conditions, paradoxically, the global PV market recently went through a chaotic time encountering the overproduction issue, the industry crisis and the long-lasting trade disputes. Furthermore, as the level of PV penetration increases, many problematics started to appear with negative systemic impacts on the electricity sector. This thesis started from these problematics to understand the PV policy mechanisms and the context change. In order to define those issues, a systemic approach is taken to provide an accurate comprehension of the overall mechanisms of PV public policies. The concrete systemic vision of PV policy mechanisms is constructed based on theoretical and historical analysis by defining key variables and the context (Part I). A retrospective analysis using the proposed mapping tools is conducted to understand critical limits and challenges of PV development and to identify risks factors in the sector (Part II). This thesis also demonstrates how the nature of policy context changes in combined with the dynamic features of the PV sector. This helps anticipate possible risks of PV development in the future. The thesis highlights the nationwide PV policy dynamics was broken with the arrival of China in the PV sector. Taken the defined critical limits and challenges into account, this thesis eventually proposes strategic orientations of PV development at the two dimensions from both national and international perspectives (Part III). At the national level, this thesis discusses on PV self-consumption as the natural way of PV power use in the electricity system. This analysis implies a change in the nature of PV policies in the future; they would evolve towards a regulation role to control systemic impacts of PV integration in the electricity system. Next, as a response to the current global industry crisis, the thesis proposes opportunities of international collaborative actions to create new PV demand in the international context in pursuit of global economic and environmental benefits.

Keywords: International Cooperation, International Trade, Globalization, Market Dynamics, Prospective Analysis, PV Integration, PV Policy Mechanisms, PV Self-consumption, Solar Energies, Solar PV Economics, Strategic Trade Theory, Systemic Approach

Résumé

Ces dernières décennies, le changement climatique a été l'objet d'importantes négociations internationales. L'énergie solaire photovoltaïque (PV) a attiré l'attention de nombreux gouvernements en étant l'une des technologies favorites pour la transition énergétique bas carbone dans la communauté mondiale. Le marché des systèmes PV a connu une forte croissance cette dernière décennie soutenue par des actions politiques favorables dans un contexte de transition énergétique. Pourtant, malgré ces conditions bénéfiques, le marché mondial du PV a paradoxalement traversé une période chaotique rencontrant des problèmes de surproduction, une crise industrielle et des différends commerciaux durables entre pays. Par ailleurs, alors que le niveau de pénétration du PV dans le mix augmente, plusieurs problématiques ayant un impact systémique négatif sur le secteur de l'électricité ont commencé à apparaitre. Cette thèse part de ces problématiques et tente de comprendre les mécanismes des politiques PV et le changement de contexte. Afin de préciser ces questions, une approche systémique est utilisée pour fournir une compréhension correcte des mécanismes généraux des politiques publiques PV. Une vue d'ensemble systémique concrète de ces mécanismes est construite sur la base d'analyses théoriques et historiques en définissant les variables clés et le contexte (Part I). Une analyse rétrospective utilisant des mappings construits pour l'occasion est conduite afin de cerner les limites et défis critiques du développement du PV ainsi que les facteurs de risque du secteur (Part II). Cette thèse montre également la façon dont la nature du contexte politique change en liaison avec la dynamique du secteur PV. Cela permet d'anticiper les possibles risques à venir pour le développement du PV. La thèse met en évidence que la dynamique nationale a été brisée par l'entrée de la Chine sur le secteur PV. En prenant en compte les limites et défis critiques définis auparavant, la thèse propose au final des orientations stratégiques pour le développement du PV selon deux dimensions, nationale et internationale (Part III). Au niveau national, la thèse s'intéresse à l'autoconsommation PV en tant que manière naturelle d'utiliser l'énergie PV dans le système électrique. Cette analyse montre un changement de nature des politiques PV dans le futur : elles devraient évoluer vers un rôle de régulation afin de contrôler les impacts systémiques de l'intégration du PV dans le système électrique. Pour terminer, afin de résoudre la crise industrielle actuelle, la thèse présente des possibilités d'actions internationales en collaboration pour créer une nouvelle demande PV dans le contexte international en recherchant des bénéfices économiques et environnementaux au niveau mondial.

Mots clés : Coopération Internationale, Commerce International, Mondialisation, Dynamiques de Marché, Analyse Prospective, Intégration PV, Mécanismes de Politique PV, Autoconsommation, Énergies Solaires, Économie du Solaire PV, Commerce Stratégique, Approche Systémique

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Abbreviations

BAU	Business as usual
BOS	Balance of System
c-Si	Crystalline Silicon
CSPE	Contribution au Service Public de l'Électricité (France)
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Act) (Germany)
FIT	Feed In Tariff
GHG	Greenhouse Gas
LCOE	Levelized Cost Of Electricity
Li-ion	Lithium-ion (battery)
SWOT	Strengths, Weaknesses, Opportunities and Threats
O&M	Operation and Maintenance
PII	Permitting, Inspection and Interconnection
PV	Photovoltaic
R&D	Research and Development
T&D	Transmission and Distribution

Institutions

CEA	Commissariat à l'Énergie Atomique et aux Énergies Alternatives (France)
COP	Conference of Parties
CRE	Commission de Régulation de l'Énergie (France)
EC	European Commission
EPIA	European Photovoltaic Industry Association
EU	European Union
IEA	International Energy Agency
IEA PVPS	International Energy Agency – Photovoltaic Power Systems Programme
INES	Institut National de l'Énergie Solaire (France)
IPCC	Intergovernmental Panel on Climate Change
IRENA	The International Renewable Energy Agency
NREL	National Renewable Energy Laboratory (the U.S.)
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of Petroleum Exporting Countries
RTE	Réseau de Transport d'Électricité (France)
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WEC	World Energy Council

Units

kWh/kWp/year	Energy produced in kilo Watt hour by a 1 kWp solar panel during 1 year
Wp	Watt peak (power)

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Introduction

1 Context

1.1 A growing interest in solar energy in the international context

Energy is a fundamental element of socio-economic development. The access to cheap energy without any interruption is thus closely associated with the modern society's development. Stable energy supply for societal needs at least costs are the government's main focus area in energy policy.

In the 1970s and early 1980s, solar energy gained the international attention in the global energy security context. At that time, renewable energies like wind power and solar photovoltaic (PV) energy began to be highlighted as alternative energy sources faced with the huge increase in the price of oil caused by the OPEC oil embargo (1973) and the Iranian hostage crisis (1979). In this regard, several countries have developed solar energy putting great efforts into research activities. However, the interest has declined in the 1980s with the expansion of nuclear power and the decline in oil prices.

The increasing awareness of environmental issues and problems (IPCC, 1990; 2007b; Chevalier, et al., 2012) has led to the heightened interest in renewable energies including solar energy. Over the past decades, climate change has been a subject of serious international negotiations. The international negotiations on climate change have evolved over the last few decades from the establishment of the basic framework of governance (the United Nations Framework Convention on Climate Change, UNFCCC) (United Nations, 1992) to legally binding agreements on climate change like the Kyoto Protocol (1997) and the Paris Agreement (2015). The use of renewable sources was recommended as an adaptation strategy of climate change. Solar PV energy is considered as one of the key mitigation technologies of decarbonized energy supply (IPCC, 2007c). According to IEA's hi-Renewables scenario (hi-Ren), 16% of world's electricity would be supplied using PV energies by 2050. This means the installed PV capacity will achieve 4,674 GW in 2050 [1] (IEA, 2014; 2014b).

The Paris Agreement (2015) took further actions to prepare the international efforts to reduce risks and the impacts of climate change by limiting global warming to well below 2°C by 2100 relative to preindustrial levels (COP21/CMP11, 2015). It acknowledged the need to promote all-inclusive access to sustainable energy in developing countries through the enhanced deployment of renewable energy. It also recognized the important role of providing incentives for emission reduction activities, including tools such as domestic policies and carbon pricing. Furthermore, the transition to low carbon energy supply system must not threaten food production (COP21/CMP11 Op. cit. article 2). In this context, solar power has caught the eyes of many governments as one of the front-runner technologies for the low carbon energy transition in the global community.

[1] IEA scenarios look into various technology solutions that can contribute to limit climate change to 2°C: e.g. improvement of energy efficiency, increase of the share of renewable energies, expanded nuclear power and CCS technologies.

1.2 The development of solar photovoltaic power

Since the mid-2000s, the PV sector went through a period of rapid change driven by public policies to support the PV applications. Over the last decade, the cost of PV modules has been sharply reduced from about 4.5$/Wp in 2005 to 0.61 $.Wp in 2015 (IEA PVPS, 2005; 2015; Lazard, 2014). Therefore, the most competitive utility-scale solar PV's LCOE[2] has fallen to around 80$/MWh in 2014 (IRENA, 2015) from about 350$/MWh in 2005. The LCOE of decentralized solar PV systems across residential and commercial segments has also been largely reduced. The LCOE of PV system in German residential sector has been reduced to under 20$/kWh in 2014 (IRENA, Op. cit.). The socket parity for solar PV power was reached in 2013 in many countries like Germany, Italy and the Netherlands (IEA, 2015d).

The global PV supply has demonstrated a rapid market growth with respect to the world's cumulative installed capacity, rising from 1.2 GW in 2000 to 178 GW in 2014 (Solar Power Europe, 2015)[3]. In recent years, the world added more solar PV capacity than the last four decades. PV power provided about 250 TWh electricity in 2015, this accounted for roughly 1% of the world electricity production (Jäger-Waldau, 2015).

Europe has taken the leading position in the global PV market, with Germany in pole position. However, Europe is losing its leading position in the global market over the last several years. There was a paradigm change in the global PV market since 2013; new growth was implemented in non-European countries (China, Japan, US). More than 60 % of new installations in 2013 came from China, Japan and the USA.

From the industry perspective, since the mid-2000s, the increase in demand in line with policy supports in Europe has attracted new producers like Chinese players into the PV manufacturing market. Chinese production soared in a short time and managed to quickly reduce the PV cost. The country now dominates the global PV market. China's rapid market expansion has brought unexpected results destabilizing the global PV market. Europe and the U.S. decided to impose anti-dumping duties on the Chinese solar panel imports and this caused trade retaliation from China. The long-running trade conflicts over solar PV products still continue.

2 Problem statement and objectives

Solar resources are available everywhere without any geopolitical conflicts over natural resources. In addition, PV power has few technological risks with the advantage of being able to provide decentralized power. As said, solar photovoltaic market has demonstrated a constant growth supported by favorable political aids in the energy transition context. The PV prices have sharply reduced benefiting from economies of scale in recent years. However, despite these favorable conditions, paradoxically, the global PV market went through a chaotic time encountering the industry crisis with bankruptcy of many PV firms and long-lasting trade disputes. Furthermore, as the level of

[2] The levelized cost of energy (LCOE)
[3] Solar Power Europe, formerly known as EPIA (European Photovoltaic Industry Association)

PV penetration increases, many problematics started to appear like financial impacts on conventional power plants and negative wholesale price of electricity. This thesis started from these problematics. What happened in the PV development mechanisms? What led to this situation?

Most researches in recent years aimed to anticipate or respond to issues related to very specific matters like the financing for PV growth or PV impacts on electricity system. These kinds of research studies are often associated with technical solutions to the given question. These approaches are very essential to prepare for further PV growth. However, policymakers need a more holistic point of view to decide strategic orientations for the PV development in the future energy system.

In this regard, this thesis attempts to analyze the PV public policy mechanisms with a focus on the relations between different sectors that constitute the PV system. The objectives of this study are as below:

- To provide policy decision makers or policy evaluators with policy evaluation tools that give a macroscopic perspective (a big picture) and a detailed view of the sequence of PV system,
- To analyze the complex and dynamic features of PV policy mechanisms by taking the policy context and its historicity into account: this eventually helps understand causes of problems and the mechanisms behind them,
- To propose strategic orientations for PV growth; this aims to improve the overall performance of PV policy mechanisms in the energy system with increased satisfaction of the main stakeholders as a whole.

3 The development of solar PV energy in the literature

This thesis discusses on the public policies for the development of solar PV power and its impacts on technology systems and market dynamics. The thesis aims to contribute to bring a new scientific approach based on the systemic analysis of public policies for the development of PV power.

The relevant literature on policies in support of solar PV power development is very large because the subject concerns many fields (e.g. technology, public policies, innovation policy, economics, environment policy, and electricity market). In this part, it does not attempt to cover all the existing literature, but it aims to provide an overview of key selected literature of the relevant subjects in the PV sector by highlighting the different research areas of interest.

3.1 Theoretical justification of government intervention to develop renewable energies

The overview of literature on public policies in favor of PV power should trace back to the theoretical literature on the justification of the government's intervention to develop renewable energies in pursuit of low-carbon energy transition (United Nations, 1992). The concept of environment has changed over time from an external element of production model to an important factor in the socio-economic growth model. However, the paradigm shift is quite limited without any political favor. Many studies thus advocated government intervention via public policies of innovation to enhance innovation capabilities to shift towards a more sustainable paradigm (IPCC, 2011b).

From an economic theoretical perspective, the government intervention can be justified when it aims to resolve market failure to obtain a more efficient outcome and to redistribute income at the socially optimum level than the result from free market system. Such market failure is related to innovation and R&D activities to develop renewable energies. The output of R&D investment can partially be considered as public goods: non-excludable and non-rivalry in consumption (Arrow, 1962; Mamuneas T.P., 1996). In some circumstances, private firms invest below the socially optimal level with the aspiration of benefiting from other firms through knowledge spillovers (Griliches, 1992); this would reduce social benefits (Jaffe, 1986). Therefore, government intervention can be justified to increase innovation. This also closely related to the national industry competitiveness.

Government intervention is also necessary to internalize externalities of environmental costs (Pigou, 1920). Even though a firm that generates pollution to produce its products harms social benefits, the private sector has little incentives to reduce negative externalities. Such negative externalities are not correctly reflected in market prices (Baumol & Oates, 1988). Government can intervene to correct negative externalities related to the environment through various methods like carbon taxes, emission trading schemes or regulations (Solangi, et al., 2011). Otherwise, the self-interest seeking firms would not concern global warming or pollution issues unless the external cost is internalized (IPCC(b)).

3.2 Review of relevant literature of PV policies and PV development

Literature review with a specific angle on PV policies and PV development can follow diverse orientations because it embraces many research subjects. Table I summarizes the major domains of researches concerning PV power development in the energy system.

Some studies have provided well-defined summaries of PV technologies and usages and their historical evolution (IEA-ETSAP and IRENA, 2013). Since this thesis is mainly focused on PV public policy issues, the advanced analyses on PV technologies are not considered.

In the past, PV policies mainly aimed to increase the performance of basic science technology; PV innovation was thus mainly driven by the government policy like patent protection, R&D tax credit or R&D funding. Researchers studied the necessity of policy support to advance the innovation of PV technologies (technology-push) (Schuster, 1981). The private sector has difficulties to invest in new energy technologies at its early stage of development. Some literature explained the difficulty to integrate renewable energies in the existing energy system: the carbon-intensive energy technologies have organizational advantages benefiting from economies of scale (carbon lock-in) (Unruh, 2000) and there are barriers related to the contextual reason like increased lobbying against new renewable technologies (Hughes, 1986). Therefore, public policies have the significant role in removing such barriers to the PV developments. However, despite the public support to R&D activities, the PV technologies still remained expensive compared with other energy technologies. PV power was first seen as technical solutions for the electrification in remote areas or consumer electronic use (the World Bank, 1996; Hoffman, 2006).

	Focus areas	Selected literature
Supply-side	Technology : e.g. R&D activities related to the PV development	(El Chaar & El Zein, 2011), (Green, 2005), (IEA-ETSAP and IRENA, 2013), (IEA, 2014), (IPCC, 2011c)
Innovation	Innovation studies : e.g. innovation trajectories	(Watanabe, et al., 2000), (Nemet, 2009; 2012), (Neij, 1997), (Van Benthem, et al., 2008), (Finon, 2008)
Demand-side	PV usages: e.g. history and evolution of PV usages	(Hoffman, 2006), (IPCC, 2011c) (Haas, 1995)
	PV integration: e.g. issues around PV integration in the energy system	(Haas, et al., 2013), (OECD/NEA, 2012), (Pudjianto, et al., 2013), (Ueckerdt, et al., 2013)
	Coupling with other sectors	(Kempton, 2015), (Ajanovic & Haas, 2015), (Popiolek, 2015b)
Public policies	Role of public policies: e.g. general explanations about public policies in support to PV power	(Byrne & Kurdgelashvili, 2011), (Timilsina, et al., 2012), (IRENA, 2012b), (IPCC, 2011a), (IEA, 2014)
	Country studies: e.g. PV policy review of selected countries	Germany: (Lauber & Mez, 2004) Japan: (Kimura & Suzuki, 2006) China : (Zhang & He, 2013) Comparative analsysis : (Avril, et al., 2012; Shum & Watanabe, 2007; Grau, et al., 2012; Solangi, et al., 2011)
	Evaluation of policy instruments	(Wüstenhagen & Bilharz, 2006), (Menanteau, et al., 2003), (Lipp, 2007), (Jacobsson & Lauber, 2006)
Multi-disciplinary	Institutional changes: e.g. green growth	(Edquist, 1999), (Rotmans, et al., 2001), (Jouvet & de Perthuis, 2012), (Lee, 2010)

Table I: Major domains of researches concerning PV power development

From the 1980s, many governments started to take effect innovation policy putting the focus on commercialization. In the 1990s, the contribution of the PV energy in the society began to be focused under the energy transition context. Accordingly, researches on PV development began to include market perspective. For example, the simultaneous employment of both R&D policy and deployment policy can bring the best results of innovation (Mowery & Rosenberg, 1979). Neij used the learning curve theory, which describes the relation between the reduction of production costs and accumulated experiences along with the production volume growth, to demonstrate the important potential reduction of PV production costs (Neij, 1997). Haas analyzed PV usage highlighting the importance of the increased consumer's participation through the deployment of decentralized PV systems (Haas, 1995). He advocated the government's promotion strategy (e.g. the roof-top program in Germany and Austria) for the widespread use of many small PV systems to seek for sustainable energy conservation effects due to a change in consumer awareness (Haas, 1994; 1995; 2003).

Studies also began to analyze the relation between technology innovation and demand creation or to compare them with the objective to increase PV competitiveness. Grubb asserted that the proper liaison between technology energy solution and market opportunities helps promote technology innovation (Grubb, 2004). In addition, synergies or positive feedbacks between R&D and deployment policies were suggested by many researchers. For example, Watanabe's 'virtuous circle' provided a theoretical support to the country's policy initiative to create technology innovation process. He asserted the creation of 'virtuous cycle' between R&D, market growth and price reduction for PV development based on an empirical analysis of Japan's PV development (Watanabe, et al., 2000). Nemet examined the most important factors in reducing the cost of PV modules in the past based on empirical data (Nemet, 2006). He also compared between demand-pull and technology-push policies in terms of PV technology change (Nemet, 2009).

In the 2000s, several governments decided to stimulate the PV demand. Researches mainly focused on the effectiveness of demand-side policies. The serious PV demand-side policy support was started with the feed-in tariff (FIT) system in the early 2000s. Germany became the largest installer in the world supported by this policy method since 2004. Studies began to focus on analyzing the initial results of this policy instrument. Wüstenhagen indicated the successful result in increasing the share of renewable electricity in Germany was thanks to the effective public policy, in particularly the FIT system (Wüstenhagen & Bilharz, 2006). Studies also aimed to assess different policy instruments; for instance, price-oriented policies versus quantity-based instruments (Menanteau, et al., 2003) and a comparative analysis of FIT vs. RPS (Lipp, 2007). In addition some studies provided a close up on a policy evaluation of certain countries (Jacobsson & Lauber, 2006; Agnolucci, 2006; Kimura & Suzuki, 2006) or conducted a comparative analysis of several countries (Avril, et al., 2012; Shum & Watanabe, 2007; Grau, et al., 2012; Solangi, et al., 2011). In addition, some studies aimed to give an overview of PV policies and the prospect for solar energies in the future (Byrne & Kurdgelashvili, 2011; Timilsina, et al., 2012) or to provide guidelines on renewable energy policy evalution (IRENA, 2012b). Reserches recently started to raise a question on policy costs of German PV policy (Hoppmann, et al., 2014).

Since the mid-2000s, Chinese arrival in the PV sector has surprised everyone. Researches tried to understand the impacts of this new player. In 2011, Grau studied public policies in support of PV energy development in Germany and China. He asserted the increased focus of public policy with regard to photovoltaics was placed on the national industrial policy objectives like local employment and GDP growth (Grau, et al., 2012). The issues of knowledge transfer between Germany and China were discussed by Grau and de la tour (du Fayet de la Tour, 2012).

There was an attempt to broaden the policy analysis angle towards multidisciplinary approach. According to Charles Edquist (1999), the innovation policy should assemble relevant areas like R&D, technology, infrastructure and education. In addition, it must be integrated into industrial policy. He asserted the necessity of the public intervention (e.g. regulation) for the sectors that have no market mechanism; they concerns law, educations, research, social security, environment, infrastructures, etc. (Edquist, 1999). Rotmans also showed the complexities of transition by public policy (Rotmans, et al., 2001). He indicated that the transition can be seen as a set of connected changes that occur in different sectors like technology, economy, institutions, behavior, culture etc. with multiple causality and co-evolution in several different areas. In addition, the green growth model can also be seen as a new approach with a broader vision embracing other sectors like sociology, industry and development (Jouvet & de Perthuis, 2012; Lee, 2010). The theory expanded the political context of PV development towards an economic development aspect on top of the energy transition.

The important focuses of recent researches are placed on the PV intermittency and its impacts on the network and electricity market (Haas, et al., 2013; OECD/NEA, 2012; Ueckerdt, et al., 2013; Pudjianto, et al., 2013). The former researches on PV integration mainly studied the technical solutions for the grid stability, however, the new approach started to include the overall impacts of PV integration in the electricity system including externalities. Furthermore, as promising solutions of intermittent PV power, some studies began to look for opportunities of coupling with other sectors like electric car (Popiolek, 2015b) or H_2 (Ajanovic & Haas, 2015).

Like this, PV policies concern the extensive areas and they are influenced by diverse factors. Any kind of system-wide change affects the policy mechanisms and outcomes. Therefore, gone through this literature review, we decided to provide *a systemic approach* with the objective to give complementary insights on the subject. The systemic approach includes a broader perspective to analyze PV policy system and its dynamics compared with existing approaches that provide a specific focus on certain subjects of PV policies. We also intend to study the PV policy system in liaison with globalization to define the dynamics of the PV policy system at the international level (Yu, et al., 2016). Therefore, our research would be distinguished from the existing work based on the following reasons:

- It attempts to provide a systemic vision to analyze the complex PV policy system by embracing multidisciplinary domains,
- It aims to propose analytic methods to prepare and evaluate PV public policies by taking the context and dynamics into account,
- It intends to contribute to enlarge the scope of dynamics of PV public policies mechanisms at the international level in connection with globalization,
- This systemic approach would be useful to anticipate policy risks.

4 Methodologies: a systemic approach

This dissertation aims to answer the following research questions.

1) What are the key variables and context associated with PV development and PV policies?
2) What are the critical limits and challenges related to the PV policies and what mechanisms are behind them?

Once the PV development mechanisms with critical limits and challenges are identified, the thesis aims to answer the third question:

3) Taken the current critical limits and challenges into account, what strategic orientations can help improve the PV policy mechanisms?

In order to answer those questions, it is not possible to provide an accurate comprehension of the overall mechanisms of PV public policies without a systemic approach under dynamic context. How to manage known or un-known risks related to PV development is closely associated with success of PV policies in the energy mix. Worldwide policymakers aspire to well anticipate all kinds of policy risks to avoid negative consequences. It might seem like guess work, however strategic approach exists to manage such risks. It can be done based on a combination of two techniques:

- Model the PV system by taken as many influencing factors as possible into account to provide an accurate insight into complex and diverse policy systems (systemic approach),
- Build solid knowledge tools to anticipate disruptive changes in the market and new business models; they can be constructed based on experiences that share the similarity (retrospective analysis based on systemic view).

In this regard, we decided to approach the problematics based on the systemic vision. The purpose of this approach is to establish the concrete PV policy mechanisms taken its complexity and dynamic features into account. Systemic analysis needs to broaden the scope of study to understand each segment of a system and to highlight links between sectors that are often studied separately. We try to handle most of the relevant domains that influence the PV policy mechanisms from a systemic perspective. This requires the employment of various analysis tools that fit with each sector. Therefore, this thesis combines different analysis tools to provide a systemic point of view regarding the PV development.

By keeping this global and systemic vision on PV policy mechanisms, this study is conducted in three steps: 1) theoretical analysis to define the context of PV public policies, 2) retrospective analysis to understand critical risk factors in the PV policy mechanisms, and 3) proposition of strategic orientations of PV public policies.

4.1 Theoretical analysis to define the context of public policies in support of PV energy development

The aim of this step is to address the first research question to define the key variables and context associated with PV development and PV policies. This helps construct key segments for systemic vision of PV policy mechanisms.

We first give theoretical analysis to specify the PV development system based on three axes defined in the thesis subject; PV technologies and its costs (supply-side), PV usage including the integration in the electricity system (demand) and PV policies (driving force). The rationale for public policies in support of PV power development based on theoretical analysis is presented. The systemic approach then helps us to conduct the risk analysis and stakeholder analysis to define potential policy risks and challenges.

Public policies in support of solar PV power development: The rationale for public policies in support of PV power growth in the energy system from a theoretical and a historical angle is discussed. A recall on the public policy and the role of government in the history of economic thought is presented. In addition, the theory of environmental economics is discussed. This approach narrowed down to the field of energy where the intervention of the state is a significant issue. As the concept of environment has evolved in the human society, many countries consider photovoltaic energy as one of the promising solutions to deal with challenges related to the fields of energy, environment and economic development. However, PV energy was insufficiently competitive in the market and its growth was largely dependent on the policy strategy. The government's policy choice is affected by the policy context and the historicity. The policy decision of PV integration requires the integration efforts (e.g. organizational change or designing new markets) that influence the existing energy system. Therefore, innovation theory (e.g. learning curve and the systemic innovation) was studied to provide the theatrical background of the PV development. Finally, an overview of the policy evaluation methods is made to define our choice on methodologies to give a systemic vision for our policy analysis.

PV technologies: The state of the art analysis of PV technologies with their costs in the electricity system is conducted. We mainly focus on silicon technology that dominates the current market. Our analysis covers the whole value chain of PV systems from PV cell technology to the complete PV system with battery. A particular zoom on the storage of electricity with a special attention to Lithium-Ion (Li-ion) battery is also given. It can be directly associated with decentralized PV systems and gives opportunities for a large deployment of PV systems thank to the potential cost reduction by economies of scale in the near future.

PV usages including the PV integration: An analysis on the usage of PV technologies is conducted using the method of SWOT (Strengthens, Weakness, Opportunities and Threats) analysis. This approach helps identify strong and weak points of internal resources and external environmental factors like opportunities and threats that can be faced in the marketplace. The accurate analysis on each usage is useful to propose strategic directions of the utilization of each PV usages in the electricity mix and the industry development. Our analysis is extended to include integration impacts of the intermittent PV power production on the electricity system. An in-depth discussion on critical issues related to systemic costs of PV power is provided.

Stakeholder analysis and risk analysis related to the PV development: Based on the definition of the overall context of PV policies, we eventually present the risks and the most important challenges which need to be taken into account for the development of PV (risks analysis). Furthermore, our analysis also includes the risks related to stakeholders (stakeholder analysis). With the implementation of the new mode of PV power use, stakeholders experience changes in their interests in the current energy market model. It is thus important to understand stakeholders' viewpoints with potential opportunities or threats. In doing so, strategies can be better prepared to take into account negotiations with opposing groups (if any) or to mitigate possible policy risks from stakeholders.

4.2 Retrospective analysis to understand critical limits and challenges in the PV policy mechanisms

Secondly, a retrospective analysis of PV policies in major countries is conducted. At this stage, we address the second research questions to identify critical limits and challenges related to the PV policies mechanisms and understand the mechanisms behind them.

The retrospective analysis does not give a panacea for policymaking because the replicability of policy is seldom possible with differences in policy context, historicity, and dynamics. However, it is still useful to identify known risk factors for the future policy decisions to avoid negative effects. It allows us to predict unexpected but possible risks based on data array. In addition, the cross-country analysis of PV policies based on a systemic approach allows us to understand the complexity of PV policy mechanisms and its dynamics that evolve with time. This helps provide a concrete insight into the dynamic PV policy mechanisms.

In this context, the retrospective study is conducted to examine major countries' policies and results. Germany, Japan, and China are principally focused because of their important occupancy in the global supply and demand system. France, the USA, and South Korea are also studied due to their specific features in the PV market and PV policies.

Proposed mapping methodology for the systemic analysis: As policy evaluation tools, we propose two types of mapping methodologies that help conduct the retrospective analysis; a schematic map of PV policy mechanisms that give a macroscopic vision to policymakers and the criteria of policy evaluation (detailed mappings) to find the problematic points for policymakers. The identified variables in the first step were re-organized, using the proposed methods.

It is difficult to capture the policy system in a single diagram because of its complexity. However, we aim to concisely visualize the PV policy mechanisms based on a systemic approach. Logic models are used to propose the schematic map of PV policy mechanisms. It aims to visualize how policy inputs and resources driven by policy objectives turn to specific outputs with long-term impacts on society. The model also includes key contextual factors that have an important influence on the PV policy mechanisms. A comparative country analysis using the proposed analysis tool makes the complexity of the policy system stand out; each country has different strategic policy trajectories and consequences based on different policy context and historicity. Accordingly, the importance of each variable varies among countries. The accumulated experiences and knowledges allow us to point out key variables related to PV policy mechanisms.

In the continuity of retrospective analysis, we develop the detailed mappings that explain what makes the change in the PV policy mechanisms directly or indirectly (causal relations among variables). This approach is also useful to imagine possible futures. We thus construct the detailed mappings according to a technological prospective methodology (*méthode de prospective* *technologique*) proposed by N. Popiolek (Popiolek, 2015) to help our analysis. Three mappings are constructed around each core variables of a problematic issue to conduct a systemic and complementary analysis; PV installation growth, the competitiveness of PV power (the real cost of PV electricity in the electricity mix), and economic gains through PV development.

The analysis of dynamic features and their influences: PV sector has dynamic features with rapid changes. The PV policy mechanisms are very complex and thus difficult to control because of constantly changing market dynamics. The reflection on the historical evolution of PV public policies based on the proposed mapping methodologies raises questions about the fast-changing market dynamics of PV sector by highlighting changes in the overriding factors in the PV policy mechanisms over time. The systemic analysis drives us to study the policy dynamics. We thus provide an in-depth investigation on three critical issues to highlight the dynamic features of PV policy mechanisms. First, the problematics related to FIT adjustment are analyzed. The rapid change in module prices in an open economy influenced the PV policy mechanisms. Secondly, PV systemic costs are discussed as hidden risks and challenges. Lastly, our analysis examines the impact of PV globalization on the national PV policy mechanisms. Our study attempts to extend the scope of systemic approach to the international level because the dynamics becomes greater combined with the globalization.

4.3 Proposition of strategic orientations of PV policies for PV growth

The aim of this step is to address the third question to propose strategic orientations to help improve the PV policy mechanisms. The attempt has two dimensions from both national and international perspectives. The three issues discussed in the previous step are taken into account to recommend strategic orientations of PV development with the objective to integrate the complexity and dynamic features of PV policy mechanisms.

PV integration in the energy system (PV self-consumption): At the national level, we need a new policy approach which is less costly but more suitable to the PV specificities and market dynamics. It should also bring a sustainable growth of PV installations. Taken identified limits and challenges into account, we discuss a new mode of PV usage with self-consumption model. As PV power becomes more competitive, more consumers would be willing to install the PV system for their own use to lower energy bills. In order to prepare this transition, we need strategic orientations to integrate this usage in the energy system with the least costs. In this regard, our study aims to propose strategic orientations of PV self-consumption use.

In the short-term, we study the benefits of prioritizing sectors with the best corresponding profile between PV system output and onsite demand based on French supermarket surfaces. In the longer-term, when electricity prices continue to rise while PV system prices go down, the economics of PV self-consumption model will greatly improve, making the model profitable for other sectors whose correspondence ratios are poorer, e.g. residential. The impacts would be greater when it is combined with improved storage systems. We thus estimate the future cost reduction of PV system combined with battery in the residential sector based on IEA's different scenarios. In our study, we quantify opportunities, costs, and impacts of PV self-consumption on stakeholders in the electricity market. Our study considers two time horizons- 2020 (short-term, supermarkets) and 2030 (longer-term, residential). We also investigate benefits of PV self-consumption model related to PV systemic costs in contrast with utility-scale PV systems.

Ways out of the global PV industry crisis (international cooperation): Our study provides a broader perspective on the PV policy mechanisms taken the international context (globalization) into account. We highlight the importance of external factors in the national PV policy mechanisms in an open economy. The study intends to provide a precise insight into globalization effects on the PV policy mechanisms based on the coupling case studies of Germany and China. We aim to model the complicated strategic interactions and accompanying consequences using the strategic trade theory (Krugman, 1986; 1987)**.** The change in the market equilibrium influenced by the external factors is explained using the international trade theory. We intend to analyze the relations between Chinese strategic movement and the current PV industry crisis and long-lasting trade disputes.

Once we present the theoretical analysis of the interactions of different policy strategies in the global PV market, we attempt to propose ways out of the global industry crisis based on the international cooperation to increase the global demand. We first study opportunities of solar PV electrification program in the less-developed and developing countries with the objective to give new outlets for the global overproduction of PV products and a solution to the global energy poverty problem based on sustainable socio-economic development model (green growth). In addition, we explain how this enlarged market contributes to the global PV competitiveness using the innovation theory (e.g. learning curve). Next, we also examine other cooperative political actions to enhance the PV system competitiveness in non-module sector based on the learning curve effect.

5 Structure of the thesis

The dissertation is consisted of three Parts. Each step of our approach leads to each Part, respectively.

Part I: Theoretical analysis to define the context of public policies in support of PV energy.

In Part I, we discuss the public policies (chapter 1), PV technologies and PV usages with its integration (chapter 2). Once the context of photovoltaic is precisely defined, we understand that the development of PV is limited without a policy framework. Chapter 3 thus presents the role of policy in the development of PV with a focus on IEA scenarios. IEA's suggested political efforts and movement in the development of PV power are presented. And then, a risk analysis is conducted to identify major potential risks and challenges in support of PV energy in the current and future energy system. Part I is used as a theoretical framework for applied studies in Part II and Part III.

Part II: Retrospective analysis to understand critical risks and challenges in the PV policy mechanisms

In Part II, a retrospective analysis of PV public policies is conducted using two mapping methodologies to understand critical limits and challenges of PV policy mechanisms. In chapter 1, we overview the global PV market trends and the general context of PV sector. The goal of this chapter is to define major players in the PV sector by considering both the supply and demand sides to select sample groups of our retrospective analysis. In chapter 2, we conduct a retrospective analysis of PV public policies using a schematic map of PV policy mechanisms. Next, in chapter 3, we provide an in-depth insight into relations among key variables for three important pillars of PV policies; PV electricity production growth, economic benefits through PV industry development and the reduction of PV costs. The systemic analysis using the mapping methodology leads to a study with a zoom on policy dynamics. Therefore, we finally discuss critical limits and risks of PV policy mechanisms that have emerged in the major countries in liaison with dynamic features of PV policy system.

Part III: Proposition of strategic orientation of PV policies for further PV growth

In Part III, we propose strategic orientations for PV growth. In chapter 1, we discuss a new mode of PV usage with self-consumption model. We first introduce the basic notion of self-consumption and characteristics. A stakeholder analysis is presented to understand the stakeholders of PV integration in the electricity mix before developing our case study. And then, a micro-economic case study to evaluate opportunities of PV self-consumption in French supermarkets is conducted. This case study aims to analyze the effect of PV self-consumption model to what extent the identified issues are solved with this new mode of PV power use. We then extend our case study to the longer-term perspective based on residential PV systems combined with Li-ion batteries. In chapter 2, we attempt to provide a precise insight into globalization effects on the PV policy mechanisms. Our study intends to explain how Chinese government's strategic trade policy influences the investment choices and payoffs of the market players. We explain the characteristics of the global PV market because it is important to understand the context of Chinese strategic movements and consequences. We also suggest a new game setting to think over the possibility of increased market players' profits in the future. In chapter 3, we propose strategic directions to solve the oversupply issue based on international cooperation. We first quantify opportunities of electrification in the developing countries for future PV growth and the contribution to the global PV sector. And then, we also propose the cooperative political actions to enhance the PV system competitiveness in non-module sector.

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Part I: The necessity of public policies in support of photovoltaic (PV) development

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Part I. The necessity of public policies in support of photovoltaic (PV) development

Introduction

In Part I, we aim to provide a theoretical framework to define the key variables and context associated with PV development and PV policies. This is a necessary step to construct a systemic vision of PV policy mechanisms. We thus develop the thesis subject by specifying the context according to three keywords: public policies, PV technologies and PV usage with their integration into the energy system. All the findings regarding the context of PV development in Part I provide us a broad understanding of the complicated system related to PV development. This Part consists of three chapters.

The first chapter discusses the notion of public policy from a theoretical and a historical angle. The approach gradually focuses on policies in support of renewable energies and photovoltaic energy.

The second chapter analyses the rest two issues of the subject: PV technologies and their usages. This chapter presents the state of the art analysis of PV technology systems with a focus on the silicon PV technology that dominates the current market. Then, a reflection on the usage of PV technologies is conducted using a SWOT analysis to help the policymaker's decision. In addition, the integration of PV in the energy system is studied based on a systemic approach; this enables us to take issues related to the intermittency of PV production into account. The elaborate comprehension of impact of PV power use in the energy mix is useful to prepare future strategies of PV usage.

Once the field of photovoltaic energy is precisely studied, we understand that the development of PV energy is limited without a policy framework. Chapter 3 thus presents the role of policy in the development of PV with a focus on IEA scenarios. IEA's suggested political efforts and movement for the development of PV are presented. And then, a risk analysis is conducted to identify major potential risks and challenges in support of PV energy development in the current and future energy system. Part I will be used as a theoretical framework for applied studies in Part II and Part III.

Chapter 1. Public policy, innovation policy and policy evaluation

This chapter presents a profound comprehension of public policy based on a theoretical and a historical perspective. To begin with, a recall on the public policy and the role of government in the history of economic thought are presented. This general analysis is then narrowed down to the field of energy where the intervention of the state is a significant issue. Faced with new challenges related to the fields of energy, environment and economic development, photovoltaic energy provides a solution but it is insufficiently competitive compared to conventional energies. The state intervention is thus required to develop PV energy in the energy mix. It is useful to take an interest in innovation policies to support PV development since the integration of PV energy in the energy system requires integration efforts (e.g. changes of organizations and practices or creating new market etc.), which affect the existing system. In this regard, economic theories of innovation as well as public policies that promote it are presented in section 3. This approach is applied for renewable energies where the innovation is required in the field of energy. Finally, an overview of the policy evaluation methods is made to find methodologies for our retrospective study, which will be conducted in Part II.

1 Public policy

1.1 Definition of public policy

The concept of policy has a long history probably since the beginning of civilization if it only concerns public advices. In the modern society, public policy is the government's actions to address a particular public issue, or to realize the political and administrative purposes in the future. Local, state, or federal government as well as international governmental organizations can design and take such actions to protect or increase benefits of their populations.

Various scholars have attempted to define public policies using different analytical frameworks (Akindele & Olaopa, 2004). Thomas Dye suggested a simple definition of public policy; public policy is anything a government chooses to do or not to do (Dye, 1972). According to David Easton, public policy is the authoritative allocation of values for a society (Easton, 1953); the values concern not only tangible matters, but also intangible things (Huang, 2002; Miller, 1971). Anderson considered public policy as a purposive course of action followed by government in dealing with some problem or matter of public concern (Anderson, 1975; Obo, et al., 2014). According to Dror, public policy-making is a very complex, dynamic process whose various components make different contributions to it. It decides major guidelines for action directed at the future, mainly by governmental organs. These guidelines (policies) formally aim at achieving what is in the public interest by the best possible means (Roos, 1973).

The public policy as a separated field in social sciences emerged in the sixties, embarrassing many disciplines from economics, sociology, philosophy, and political science. This modern approach to the public policy started with H. Lasswell taken into account the normative approach[4] on top of

[4] At that time, behaviorism was the dominant scientific approach to explain political situations; it aimed objectivity in gathering data and its interpretation based on quantitative methods. However, this fact-based study methodology excludes the

empirical method for objective quantification (Hildreth, et al., 2006). In his work, the policy orientation (Lasswell, 1951), H. Lasswell highlighted the policy of democracy to realize the human dignity.

According to H. Lasswell, the policy sciences have three important features. First, they aim to identify goals, trends, conditions, projections and alternatives related to real world problems in the society (problem-oriented). In addition, that process should be interpreted in the larger context of events concerned with spatial and temporal perspectives (contextuality). The policy sciences cut across other specializations to add knowledge in the process of policymaking and execution (interdisciplinary) (Lasswell, 1971). Lasswell's perspectives on policy sciences came to public attention when post-behaviorism[5] appeared in the US in the 1960s in an effort to suggest theoretical solutions to social problems in those days (the Black riot, the Vietnam War).

D. Easton also asserted a new approach in policy sciences so called 'post-behavioral revolution' (Easton, 1969). He criticized the existing behaviorism's research method because of its absence of relevance. At that time, the dominant research method based on value-free empirical method approach could not suggest practical answers to social problems even though it made rapid progress in science. Thus, he put an emphasis on the addition of creative approach based on values and normative presupposition. D. Easton also developed a theory of the Political Systems (Easton, 1957), which was considered the most imposing theoretical structure from behavioral movement in political science (Miller, Op. cit.). The political system proposed a comprehensive view of the nature of political science and political theory. D. Easton asserted that the study of politics should aim to understand how authoritative decisions are made and executed for a society and those works will be reviewed in a political life. He focused on nature and consequences of political practices through the examination of operation of political parties, interest groups, government and voting, eventually to draw rough picture of aspect of actions of those units and their interactions. The political system is used in a context of a system of interrelated activities with systemic ties when authoritative decisions are taken and executed for a society (Easton, 1957).

1.2 The role of government in the history of economic thought

There is a variety of political positions towards government's role on its public policy. The government's policy choice has largely influenced by the adopted economic thoughts of the time. The economist's view on the government's role has changed according to the times. Discussion on the government's size is determined by scope of government's intervention and role of the government when handling economic and social activities.

In the 18th and 19th centuries, the minimized government role was highlighted; the state should minimize its intervention in the market and focus on defense, foreign affairs and public security (night-watchman state). Classical economists like Adam Smith and Ricardo supported this approach.

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value problems closely connected to the public policy. The Lasswell's work proposed a new method in the science of policy.

[5] Post-behaviorism appeared against the dominance of behaviorist methods in the study of politics; post-behaviorism was against value-neutral method.

Adam Smith introduced benefits of market mechanism of resources allocation in his major work 'an inquiry into the nature and causes of the wealth of nations (1776)'. According to Smith, when participants in the market seek their own self-interest, the good of society is promoted, led by the invisible hand. He criticized the protective trade, claiming to minimize the government's roles in the market economy.

However, there is a criticism of Smith's theory. When Smith's invisible hand fails to deliver beneficial social outcomes, resources are distributed inefficiently regardless of the real values and benefits (market failure). This inefficient allocation is often discovered related to the public good, imperfect competition, asymmetric information and externalities.

The government active intervention shall be justified with regard to the principle of the correction of the situation of market failure. For example, the government's roles to enforce contracts and to protect property rights are important to maintain the market mechanism (Stiglitz, 2006). The expanded role of government was particularly emphasized when the global economy encountered the Great Depression since 1929. Most countries experienced significant depression during the 1930s, suffering from harsh unemployment, reduction in production and deflation (Romer, 1993). John M. Keynes (Keynes, 1936) clarified the cause of the great depression from inadequate aggregate demand for goods and service in his work, 'the General Theory of Employment, Interest, and Money'. He advocated that government has expanded roles in fiscal and monetary policies to overcome the economic slumps. The expanded government's expenditure increases the aggregate demand and helps stimulate the private consumption and investment. His theory supported the US's New Deal policies (1933-1938) during F. Roosevelt's presidency, which included the government's augmented spending in public work to create jobs and to revive the depressed economy.

However, faced with the oil crisis in the 1970s, a stagflation, which accompanies inflation with economic recession, has occurred. The Keynesian theory that claims the government's intervention in the market was criticized by the neo-classical economics because his approach could not suggest the solution of stagflation (government failure). The excessive intervention of government in the market mechanisms causes problems such as lack of understanding market, inefficiencies of bureaucracy, and collusive links between politicians and businesspersons. The government's active monetary and fiscal policies were thus discouraged to avoid unintended negative effects and the laissez-faire approach was again highlighted (Friedman, 1962); governments should aim to keep a neutral position in monetary policy towards long-term economic growth. To correct the government's failure, market mechanism started to be enhanced via privatization and deregulation.

Monopoly power results in high prices and creates a deadweight welfare loss. The government action and regulation to reduce market power is justified to correct such market efficiency. However, until 1980s, research into regulation was relatively sparse, mostly dealing with how the government can intervene and control pricing in the two extremes of monopoly and perfect competition (The Royal Swedish Academy of Sciences, 2014). A new scientific methods based on game theory and contract theory contributed to analyze the real policy practice; optimal regulation should be industry-specific (The Royal Swedish Academy of Sciences, 2014b; Laffont & Tirole, 2001).

2 Public policy for energy

Energy is a basic component of human life, economic activity and civil progress (UN, 2014) and thus directly associated with national security and socio-economic development. Therefore, government puts emphasis on national energy policy and the national focuses on energy vary according to the ruling ideology.

Energy policy generally concerns all activities in terms of the energy development from energy production, distribution and consumption. It aims to address present and future energy problems as well as to prepare plans and actions of energy advance path. The preparation of institutional framework is also part of energy policy.

Energy policies vary according to periodic and geographical circumstance reflecting energy-related features such as energy supply condition, economic situation, and historical backgrounds. Different stakeholders like individual, interest groups or private and public organizations influence the formation of energy public policies and the government makes the final decision (Rudnick, 2009).

Energy policies have evolved over time. As seen, the balance between market mechanism and government's role has important impacts on public policies. The decision to find the right balance between market model with free competition and regulatory model with government's intervention is a question of long standing. These two approaches should not be considered as opposite ways but as complementing methods. The principal is applicable for energy policies.

In order to find optimum approach of energy policies, both perspectives can complement each other even though the balance differs from time to time and place to place (Stiglitz, 2006). The public policies in energy can be divided into three main streams after the World War II (1939-1945) until now (Rudnick, Op. cit.) (See Table II).

Period	Driven by	Key focus areas
1940s-1970s (before oil crisis)	Strong government's intervention	Government-led investment
1980s-1990s	Market-based mechanism, economic liberalization in energy sector	Energy supply, technology choice
2000s-now	A hybrid system between market mechanism and the governmental regulative intervention	Energy security, climate change, sustainable supply

Table II: Public policies in energy sector

As said, the Keynes's revised capitalism (1936) was the backbone of public policy to deal with the post war era. The development of energy system was no exception; it was supported by the government's strategic role based on money supply and spending. The government strong intervention appeared in energy sector including infrastructure investments in many countries until the late 1970s. Furthermore, the stable energy supply was vital to support the national socio-economic development. In this sense, the technological progress of nuclear energy proposed a good solution. In the 1960s, nuclear power achieved the technological credibility and became commercially viable. The progress led to many orders for nuclear plants in electric power utilities on a routine basis by the mid-1960s and prepared the expanding use in the 1970s (Char & Csik, 1987).

However, faced with oil shocks in the 1970s, there was a critical price increase in energy and raw materials, which led to the overall inflation with the economic recession (U.S. Department of State, 2014). The government's heavy expenditures in public sector and its inefficiency became a social problem. In the 1980s and 1990s, the energy sector followed the neo-classical economic theory, putting focus on free market mechanism; the liberalization reforms and privatization in energy sector have been implemented in many countries. The government's role in energy sector was limited during this period.

In the 1990's, the globe seriously started to concern on the environmental issues and sustainable energy supply and the Kyoto Protocol came into effect in 1997. The government's role became bigger again based on a hybrid system of market-based mechanism and regulatory system. The policy focus has a different feature according to country strategic position towards the energy system.

These days, there are a few important pillars of energy policy. As **Figure 1** illustrates, energy security, energy equity and environmental sustainability can be highlighted among them. Each government has a different policy balance among three pillars based on its political strategic position. For example, while the developed countries focus on environmental concerns and climate change issues, the developing countries concentrate more on energy supply to satisfy the energy needs of much of their population. In this regard, it is sometimes difficult to define common regional or international policy since the country is reluctant to lose the national interests to achieve it.

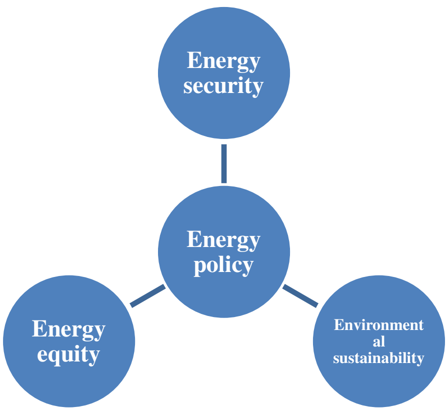


Figure 1: Energy trilemma of WEC (World Energy Council, 2014; IEA, n.d.)

- **Energy security**

Energy security is one of the most important agendas in energy policies in many countries.

Going through economic growth through industrialization and urbanization, rapid growth in population and social development, the primary energy use of fossil fuel has rapidly increased over the last centuries. However, fossil fuel is mainly supplied by Middle Eastern nations and the national economy would therefore be threatened by oil price risk, any supply disruption, or by any regional social and political unrest. Stable energy supply for societal needs at least costs became more important. The access to cheap energy without any interruption is thus important motive in the modern society's development. The following directives are often discussed to address energy security issues.

  - Secure balance of energy supply and present and future energy demand
  - Increase reliability of energy infrastructure
  - Increase energy independency by improving energy self-sufficiency
  - Diversify energy sources to reduce energy supply risks

- **Energy equity**

Over 1.3 billion people in the world are still without access to electricity (IEA website, n.d.). The energy poverty issue is another pillar to address with energy policy. Government energy policy aims to allow all citizens to afford energy service regardless of income level so as to secure the stable development and social integration. In many countries, government controls energy-pricing structure to eliminate energy poverty. In many developing countries, energy access is the primary driver of energy policies.

- **Environmental sustainability**

The transformation in energy system via de-carbonization is an important target area of energy policy. The development of modern society was mainly supported by unsustainable system accompanying concerns on natural resources and the environment issues. However, many efforts to put in place a sustainable energy system have been demonstrated supported by international governance. The following agendas are focused to increase sustainability in energy system.

  - Tackle climate change (e.g. greenhouse gas (GHG) emissions reduction)
  - Increase energy supply from renewable energy sources (or low carbon sources)
  - Increase energy efficiency

3 Public policy for innovation

3.1 Innovation in the history of economic thought

The global economy has steadily been growing in world economic history. Per capita national income has visibly increased after the Industrial Revolution in the 18th century (Maddison, 2003). The classical Malthusian approach, which asserts that marginal product of labor, becomes smaller as labor inputs increase (law of diminishing returns) on condition of unchanged land, capital, and technology, is applicable to pre-Industrial Revolution era. The Industrial Revolution led to a paradigm shift in the world economy. Under the new economic system, the world economy continues to grow in all ways. The technological progress and improved productivity enabled the world economy to support population explosion in sympathy with increase of living standard.

Innovation is one of the main drivers for the economic development with technological change and productivity gains. However, the conceptualization of innovation is a quite a recent event. Many economists began to take a profound interest in the relation between innovation and economic growth since a few centuries ago and tried to theorize them. Before Schumpeter, several literatures supported the contribution of technological progress to increase the national economy (Smith, 1776; Marshall, 1890)[6]. However, these approaches did not focus on innovation itself.

The serious discussion of innovation started since the 19th century with evolutionary economists; Veblen and Schumpeter. Neo-Schumpeterian economists (Nelson and Winter) further developed innovation theories in the context of evolutionary economic theory.

Veblen (1857-1929) highlighted the important role of the institution in innovation (Veblen, 1898; Lorenzi & Villemeur, 2009). He defines two types of institution. Dynamic technological institutions, which concern production methods, technology, or invention, give dynamic forces to advance the society. Ceremonial institutions include supporting systems to help develop technology such as socio-economic system, property rights, or practices. Both interact continuously to make a social culture change for innovation. Technology is the main factor for innovation but it alone cannot innovate; the institutions can obstacle the innovation dynamics. Accordingly, the institutions such as culture and habits need to improve or change to speed up the economic growth through innovation.

Schumpeter (1883-1950) added value in economic theories to explain innovation as a critical driver of economic growth. According to him, creative destruction is the essential ingredient of capitalist economic development (Schumpeter, 1943). It refers to ceaseless innovation mechanism by which new production units (or things) replace old ones (e.g. outdated ideas, technologies, inventories, skills or equipment). Entrepreneurs are at the center of such restructuring process and they are rewarded with profits from innovation. The technological innovation often creates monopoly rents before competitors or imitators reduce them. An entrepreneur is motivated to take inherent risks of implementing new ideas by such temporary monopolistic rents.

Nelson and Winter (Nelson & Winter, 1982) introduced the new concept of routine to explain organizational change. Routines mean all regular and predictable behavioral patterns of firm. According to them, routines are alike with gene in the social realm and it is the key element to explain the economic change (Becker, 2003; Truijen, et al., n.d.; Nelson & Nelson, 2002). Firms that have better routine via innovation are more competitive. As other firms imitate the best practices and the innovation, diffusion becomes possible via collective interaction. Like this, they suggested a broad concept of innovation on top of an individual or a firm. Innovation in organizational routines can be achieved by new combination of existing routines.

[6] According to Smith, the division of labor leads to the productivity increase that contributed to the national economic development. Smith advocated that the productivity gains are driven by the technological progress when human capital and equipment are matched in an organization.

Unlike innovation economists, neo-classical economic theories focused on the accumulation of production input factors to explain long-term economic growth. In the 1950's to 1970's, the technological progress was seen as an exogenous factor. For example, Robert Solow explained economic growth in the context of the importance of capital in the production. He asserted that increased accumulation of production inputs or technical progress stimulate economic growth. Technical change refers to 'any kind of shift' in the production function (Solow, 1957). However, he assumed that such technical change is an exogenous factor, which is decided outside the model (exogenous growth). Solow also applied diminishing returns for capital, thus concluded the endless economic growth is not achievable; after all, the accumulation of capital also faces zero marginal production at a steady state. However, this situation is different from Malthusian trap because the Solow economy has much higher living standards from the Malthusian with minimum surviving requirements. The exogenous growth model is limited to explain economic growth in a realistic way.

In the 1980's, technological change was considered as an endogenous factor for economic growth. It can be realized through innovation, R&D and investment in human capitals; positive externalities and spillover effects of knowledge will contribute to economic growth. Patents give incentive for technological progress creating temporary monopoly rents. Arrow, Uzawa, Conlisk tried to conceptualize such technological progress. Since then, the endogenous growth model seriously began by Romer (1989), Grossman and Helpman (1990), and Aghion and Howitt (1992), highlighting the role of endogenous technological progress for economic growth; learning and knowledge are positive externalities which allow to increase the productivity. Accordingly, economists concentrated on analyzing factors that influence technological progress to figure out the sustainable economic growth; Romer's learning (1986), Lucas's human capital (1988), Romer, Aghion, Howitt: R&D investments and Barro's public substructure. Human capital is important element to innovate (or to capture) or adapt new technologies (Nelson & Phelps, 1966).

In the 1990s, the conceptualization of innovation continued in the context of national innovation system (NIS). According to innovation system theory, innovation and technology development are resulted from a complex set of relationships among actors in the system; they include enterprises, universities, and government research institutions. The effective flow of technology and information among them are keys to success of innovation process on a national level.

In 2000s, innovation is seen far beyond R&D. Innovation includes commercialization, which distinguishes it from invention (Braunerhjelm & Svensson, 2007). It suggests a broad concept of innovation from changes in product to organizational methods. Innovation is defined as implementation of (Oslo manual for measuring innovation (OECD, 2005; OECD, n.d.) ;

- new or significantly improved good or service (product innovation),
- new or significantly improved production or delivery method (process innovation),
- new marketing methods involving significant changes in product design or packing, product placement, product promotion or pricing (commercialization innovation),

- new organization methods in business practices, workplace organization or external relations (organizational innovation).

Like this, the conceptualization of innovation has been developed from a long line of economists over the last decades. Referring the development process, for one thing, innovation should be reviewed based on systemic perspective (Popiolek, 2015) rather than narrow vision in order to give a holistic interpretation of innovation.

3.2 Experience curve theory

The diffusion and adoption of technologies depend on how further costs are reduced through innovation and experience accumulation (Arrow, 1962b). The experience curve (Yelle, 1979), also referred to as learning curve, describes the correlation between reduction of production cost and the level of experience (van den Wall Bake, et al., 2009).

Wright proposed the first mathematical representation of the experience curve in 1936 (Byrne & Kurdgelashvili, 2011). Boston Consulting Group then used this concept to explain how the unit cost declines with cumulative production (Boston Consulting Group, 1972; Abell & Hammond, 1979; Sharp & Price, 1990). This concept is useful to prepare the diffusion of new technologies in the market, or pricing strategies (Sharp Op. cit.).

The general rules of experience curve is that cost goes down by a constant percentage with each doubling of the total number of units produced. The experience curve is usually used for long-term strategic analysis rather than short-term tactic review; experience curve~~s~~ give a tool of projecting future cost trend based on past cost reduction (Byrne Op. cit.). The mathematical model is described in equations (1) and (2).

$$C_t = C_0 \times \left(\frac{X_t}{X_0}\right)^{-b} \qquad (1)$$

$$LR = 1 - 2^{-b} \qquad (2)$$

With:

C_t: Costs of unit production at time t (€/W), X_t: Cumulative production at time t (W)

Initial condition:

C_0 : Reference cost (the cost of the first unit produced), X_0 : Reference cumulative production

b: Experience index: this is used to calculative the relative cost reduction ($1-2^b$) for each doubling of the cumulative production

LR : The learning rate: the fractional reduction in price expected as the cumulative production doubles

The value (2^b) is called the progress ratio (PR) and used to express the progress of cost reductions for different technologies. For example, a PR of 80% means that the cost is reduced by 20% each time the cumulative production is doubled (Neij, 1997). In this study, experience curves are used to analyze possibilities and limits of cost reductions of the diffusion of PV energy technology.

3.3 Policies in favor of innovation

3.3.1 Technology-push and demand-pull

Since the 1960s, theorists have frequently debated whether successful innovation with technological change is induced by technological-push or by market-demand (Chidamber & Kon, 1994; Nemet, 2009). The first approach tends to lead to radical innovations and the latter is more adapted for incremental innovation (Sherer, 1982).

The technology proponents suggested that change in technology is the main driver of innovation. As seen, the origin of theory traces back to Joseph Schumpeter (Errabi, 2009). Since then, the technology-push model has been dominant model used to explain technological innovation for decades. It describes a situation where an emerging technologies or new combinations of existing technologies give the impetus for an innovation (Herstatt & Lettl, 2004). This means that the supply of new technologies is more important for innovation rather than adjustment the existing system of demand; only production innovation creates new industries (Coombs, et al., 1987). This approach is later known as the 'liner innovation model', which explains the progressive steps of innovation from basic science to applied research to production development to commercial products.

However, there is a criticism against the technology-push theory because it ignores prices and other changes in economic conditions that affect the profitability of innovations (Nemet Op. cit.). In addition, the approach mainly refers to innovation process in a single direction, thus is not sufficient to explain the following works that include feedbacks loops and various interactions between innovation and diffusion (Freeman, 1994).

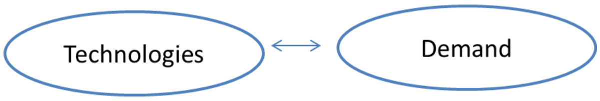
In the 1960s, the theorists' approach on innovation started looking at technological innovation from a demand-side rather than a supply perspective (Godin & Lane, 2013). The market demand school of thought asserted that organizations innovate driven by market needs.

A market-pull (or demand-pull) implies a case in which the market demands an innovation in products or service type; producers deliver the products in response to an identified but unsatisfied customer needs in the market place. Jacob Schmookler is generally referred to as the exponent of demand-pull theory of innovation. According to him, needs determine the dynamics of the invention (Errabi Op. cit.). Schmookler did not argue that demand is the only force for innovative activities. He considered invention and demand as two interacting forces of innovation (Coombs Op. cit.). The important role of scientific discoveries remains and demands influence the level of investment in R&D. However, he did not justify the arguments via empirical studies (Errabi Op. cit.).

The demand-pull approach is criticized by its broad concept of demand; it has inconsistent definition in various empirical studies (Mowery & Rosenberg, 1979) (Nemet, Scherer, Op. cit.). In addition, it is extremely difficult to measure how effectively firms identify unsatisfied needs in the market place (Nemet Op. cit.).

Like this, technology-push argument is limited to reflect the market condition in terms of innovation process while as demand-pull approach underestimates technological capabilities. Taken the limits of both methods, a hybrid technique is necessary in order to better explain the nature of innovation.

Therefore, the interaction of technology and market mechanisms should not be ignored; a good internal coupling opportunity between technology-side and demand-side is important for successful innovation (Freeman Op. cit.).



3.3.2 Innovation policies

Innovation policy was referred as various terms such as science policy, R&D policy, or technology policy. However, innovation policy should distinguish from technology policy. Technology policy is a narrow concept; it aims at affecting the actions of agents in a system, in terms of their choices of technology and the creation of new technological products, processes or services (Cowan & van de Paal, 2000). In the past, innovation was mainly driven by the government policy aiming to develop basic science technology.

However, in the 1980s, many governments started to take effect innovation policy putting the focus on commercialization with the objective of improving the national economy. Like this, innovation policy gives an equal importance on organizational change through political actions. The European Commission (EC) defines innovation policy as a set of policy actions to raise the quantity and efficiency of innovative activities, whereby 'innovative activities' refers to the creation, adaptation and adoption of new or improved products, processes, or services (Cowan Op. cit.). The commercialization or adaptation of market needs is necessary for such innovation process.

However, P. Dasgupta (1987) asserted that surprisingly, theoretical economists working in the field of technological change have not shown much passion for issues in public policy. The push-pull debate can be extending up to policy perspective; however, studies agree both technology-push and demand-pull policy instrument are necessary for successful innovation of new energy technologies (Grübler, et al., 1999; Peters, et al., 2012).

Technology-push public policies mainly aim to reduce per unit cost of production via innovation. To give an example, they include support in R&D, tax credits for companies, enhanced education or training as well as demonstration funding. On the other hand, demand-pull public policies attempt to raise returns of innovation implementation in the market place. The policy instruments include tax rebates or credits for consumers, government procurement (Edler & Georghiou, 2007), technology mandates, and regulatory standards. The types of policy instrument are discussed in the following section.

3.4 The necessity of innovation policies for the development of renewable energies

3.4.1 New approach towards the environment

In order to give more exquisite approach on the government intervention to promote renewable energies, it is important how the concept of environment in our socio-economic development model has evolved.

To do that, a quick review of standard concepts on economic growth and the natural capital should be preceded to distinguish differences from a new approach towards the environment. Neo-classical economic growth theory defines a production function based on both labor and capital (or, according to more recent studies, as a function of human capital and productive capital). On the other hand, Solow (1956) specified a growth model that explains per capita growth as a consequence of the technical progress. This progress is seen as an external growth factor A of the production.

Y = A f (L, K) *(Y: production, A: external growth factor, L: labor, K: capital)*

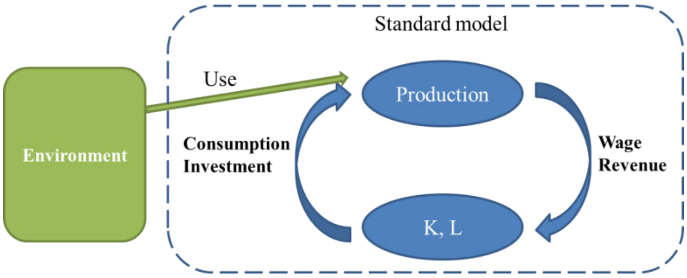


Figure 2: Standard production model

The technical progress is an exogenous factor; hence it does not directly link to productivities of labor or the capital, and another technical progress. The technical progress is rather induced by policy or investments.

New growth theories have tried to include the technical progress in the production function as an endogenous factor. However, above approaches consider environmental as an external element**; the notion of environmental use was hided and the environment is seen as an exogenous variable used for production** (see **Figure 2**).

The classical growth model has no actions to protect environment; the more the production rises, the more natural resources are needed. Assuming there are decreases of exhaustible resources and more pollutions, total output will be reduced as those situations can degrade growth factors in the long run. In this regard, based on the classical growth concept of the environment, the long-term economic growth is quite limited.

Accordingly, another expanded approach, which aims at internalizing externalities including the environment in the model (e.g. carbon tax), can be introduced by trying to isolate effects of environment in the production function. Public policies have an important role for this. In fact, the perspective on environment has a significant change going through a series of environmental events based on the international governance; it has varied from a set of fossil fuels to renewable energies sources, as well as from pollution to global warming.

The first attempt to take the environment into account was to study issues of the non-renewable resources to respond the famous report of the Club of Rome 'the Limits to the Growth'. Many studies in the mid 1970's have stated that technical progress or the substitution between the production factors could always give a solution to the scarcity of natural resources (Jouvet & de Perthuis, 2012). This optimistic vision of the growth was debated when the world became aware of the danger induced by the destruction of environment. Instead of exhaustible resources, the pollution was taken as a new factor. Now, several different models exist depending on the central theme of the study: GHG emissions, renewable energies, or environmental quality.

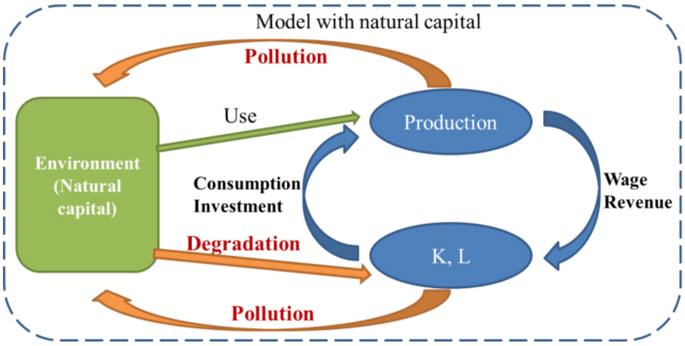


Figure 3: Model with natural capital

The classical economic model has a cycle that human and physical capitals are used for the production, and the benefits of the production are redistributed to maintain and grow those factors. By extension of this concept, the economic models integrates the environment in the production circle, and in the same context, the benefit of production generated as a result of using the environment will be re-distributed to improve the degraded environment in the production process. In this case, **the environment is seen as natural capital**, which can be used and has to be preserved. The devaluated natural capitals, by the use of production or by pollution, can be restored naturally or with human helps to sustain the production circle.

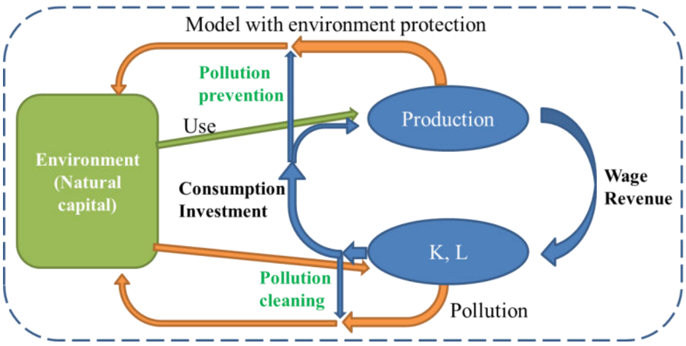


Figure 4: Model with environmental protection

Based on the production method which uses environment without consideration on its protection and restoration, the degraded environment gives negative impacts on input factors K and L, and they would become more serious to the extent that all systems are inefficient in the long run. The simplest way to prevent those expected damages is to use a part of the benefits of the production on purpose to clean or to prevent those pollutions.

However, the problem of this model is raised around the price to protect the environment. It adds another heavy load on the economy and degrades its competitiveness in the short term, in particular towards the global market, when some countries have no protection actions through public policies against pollution. This problem would not disappear as long as the production mechanism that harms the environment stays. Based on this perspective, the modification of production mechanism can be thought; **a shift towards a more eco-friendly production and consumption patterns** is an efficient way to decrease negative environmental consequences. That is the basic principle of the green growth.

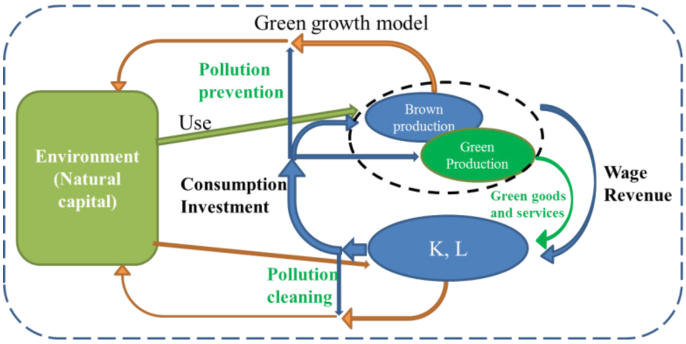


Figure 5: Green growth model

Green growth model is based on this concept of establishment of green socio-economic mechanism to provide each individual member of the community with better quality of life. The political strategy aiming to shift to a new mode of green growth model is important for the successful implementation. It aims for sustainable growth on a green basis of those production and consumption mechanisms; hence it wants to build solid 3 policy pillars which are economic growth, social advancement (equity) and pro-environment (preservation of resources, anti-pollution) (NRCS (National Research Council for Economics Humanities and Social Sciences), 2010). In this context, public policies aiming to stimulate renewable energies in their energy system can be further studied.

3.4.2 Government's intervention to develop renewable energies

According as the concept of the environment has changed, the human society began to include the environment in their socio-economic growth model. However, such movement is limited without political favors; government intervenes via public policies of innovation to enhance innovation capabilities to shift towards a more sustainable paradigm.

Neo-classical economists considered this movement to address market failures and institutional economist saw it to respond institutional failures. The choice of public policy can be justified when the aim is to increase social benefits.

According to the IPCC's special report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2007; IPCC, 2011b), the rationale of policies of energy transformation towards renewable energies ultimately wishes to improve quality of life (e.g. health, life expectancy and comfort) and productivity in a society (Hall et al., 2004, IPCC Op. cit.). The benefits of energy transition toward renewable energies can be defined as below (IPCC Op. cit.).

- Reduce CO_2 emissions
- Deliver an eco- friendly system which improve health benefits
- Increase the energy access, particular in rural areas
- Enhance the energy security via diversification of energy technologies and resources
- Bring a social and economic development

However, there is a distinct difference in decision making of investment in renewable energies between the private sector and the government; the former is motivated to invest in renewable energies mainly for profit seeking, but the latter aims to improve social welfare. Therefore, finding the optimal balance between market mechanism and government's intervention is important in support of renewable energies.

As seen, the government can intervene to **resolve market failure** and **realize internalization of externalities**. In some circumstances, the private sector invests below the socially optimal level and the government's role is significant in terms of correcting such market distortions.

The first situation concerns **market failures related to innovation** to develop renewable energies. The outputs of R&D investment can partially be considered as public goods: non-excludable and non-rivalry in consumption (Arrow, 1962; Mamuneas & Nadiri, 1996). The knowledge from R&D activities is spilled over to other industries, firms and countries and this contributes to the productivity gains (positive externalities). These effects of knowledge spillovers reduce incentives of private firm's R&D activities with the aspiration of benefiting from other firms (technology learning), and this would create negative effects to social benefits (Jaffe, 1986). The government's intervention can be justified to correct this kind of market failures in developing technologies in renewable energies.

The second situation is related to **externalities of environmental costs**. A firm that generates pollution to produce its products harms social benefits and the society will pay the cost to reduce the damage (negative externalities). However, the private sector has little incentives to reduce negative externalities when there are no economic incentives. The government attempts to correct negative externalities related to the environment through various methods such as regulations, subsidies, or market-based policies (Mankiw 2010). Otherwise, the self-interest seeking firm would not consider global warming or pollution issues unless the external cost is internalized (IPCC, 2011b; Pigou, 1920). In this context, PV policies in support for renewable energy sources aim to address externalities in terms of environmental quality, human health, economic development, or institutional objectives such as emission growth management (Solangi, et al., 2011).

3.4.3 Policy instruments to support renewable energies

In the early 1990s, only few countries had rolled out policies to promote renewable energies. The production of electricity using renewable energies got greater attention due to the increase in fossil fuel prices and concerns over greenhouse gases and global climate change issues (Bhandari 2009 (Chevalier, et al., 2012). Faced with increasing interests and concerns towards a sustainable development and environment, since the early and mid-2000s, policy started to focus on renewable energies as one of the promising energy solutions for the energy transition and deployment policies for them have emerged in many countries at the municipal, state, provincial, national and international level (IPCC, 2011a).

Policies in support of renewable energies mainly aim to have more sustainable and secure energy systems by improving the cost-competitiveness in renewable technologies and sustainability in domestic energy production and concern its market share growth and job creation (IRENA, 2012b). The government has a crucial role to advance technologies and deployment of renewable energy technologies.

However, as seen in the previous section, policies to stimulate innovation should not be confining to R&D stage only; they should also include efforts in commercialization and market development from demonstration and pre-commercialization to the large-scale stage (IPCC Op. cit.).

There is no globally agreed list of renewable policy options; they can be defined in a variety of ways (IPCC Op. cit.). According to IPCC special report, the government support policies can be categorized into three groups; fiscal incentives, public financing, and regulations (IPCC, 2011b).

- **Fiscal incentives** : reduction of actor's contribution to the public treasury through tax deductions (such as income tax or other taxes), rebates, grants
- **Public financing**: public supports such as loans, equity, or finical reliability such as guarantee
- **Regulations**: rules to guide or control

The possible PV policies instruments are captured through a literature review and re-organized in **Figure 6**. As mentioned above, they are divided by fiscal incentives, public financing and regulations. In addition, policies in support for electricity generation using renewable energies sources are divided into supply-side and demand-side (Alloisio, 2011; Finon, 2008). Both policies influence the development of manufacturing industry; the former directly aims to develop manufacturing industry (technology-push) and the latter indirectly stimulates to expand it (demand-pull) (Alloisio Op. cit.).

- **Technology-push (supply-side) policies** to support R&D via technology and industry policies (e.g. subsidies to R&D, subsidies to investment for demonstration)
- **Market-pull (demand-side) policies** to give incentives for diffusion of solar PV energy such as subsidies to electricity production and the demand (e.g. the feed in tariffs (FIT) system at technology deployment phase to crease the demand)

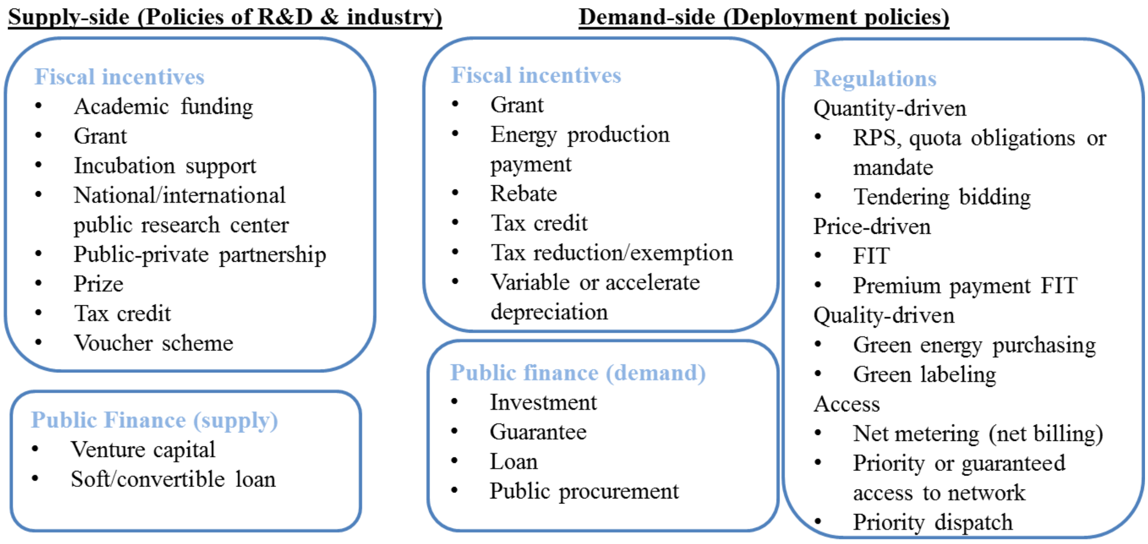


Figure 6: Policy instruments in support for renewable energy development (see annex)

4 Policy evaluation

4.1 Definition of policy evaluation

It is important to first outline the concept of ‘policy evaluation’ in order to develop the methodological technique of this study. In the modern society, the scope of government’s intervention is indeed widespread and the development process is complex. In addition, the potential consequences usually have great impacts on the national operation. Therefore, there is an increased need for the social and scientific research that oversees the national operation and demonstrates the impacts in the policy cycle. In this context, policy evaluation implies the careful assessment of public intervention based on the meaning of thinking backwards for a better future.

Policy evaluation is conducted to examine the policy content, policy implementation and policy impacts with the objective of improving the planning and implementation process in the public policy cycle. The policy evaluation can be conducted during the policy making process to draw the best results of policy formulation. However, policy evaluation is often used after the policy is implemented; it concerns an assessment and a feedback process to figure out to what extent the desired policy objectives are met and their effects (Patton & Sawicki, 1993).

In addition, policy evaluation also examines resources employed and identifies *the factors* related to successful or unsuccessful outcomes. A series of such tasks are called a *retrospective assessment* (Vedung, 1997). Evaluation enables to distinguish advantages, unities and values of public policies (Scriven, 1991). The government needs value criteria to make the division between pluses and minuses of the government interventions.

Policy evaluation helps accumulate knowledge from experiences of success and failure. The scope of evaluation varies according to the evaluator’s focus; it can restrict to narrow assessment of direct results of policy and effects, or apply a more comprehensive focus in an attempt to analyze context and environment of policymaking or implementation and impacts to the society. Going through this process, the evaluation helps decision makers take wise choices for future actions (Weiss, 1973).

4.2 Development process of policy evaluation

The developmental pathway of policy evaluation showed a different aspect according to the country (Descy & Tessaring, 2005). The policy evaluation development demonstrated a practical evolution to reflect the needs of the times. The practical start of program evaluation is around the turn of the century (Rossi, et al., 2003). After the World War II (1939-1945), the policy evaluation was developed mainly in Anglo-Saxon and Northern European countries. The adaption of systematic and scientific methods in policy evaluation is a recent event. The development history of policy evaluation can be divided into roughly three phases; the first wave of evaluation during the 1960s and 1970s; the second wave beginning in the mid-1970s; and a third one setting in since the 1990s (Wollmann, 2005).

The serious first phase of evaluation development started with the appearance of the welfare state during the 1960s and 1970s. The government encountered the necessity to foster its ability for proactive policy-making process that uses modernized political and administrative systems when assessing various social programs. The evaluation had its importance to justify the policy decision making and to gather information for the future policy design. In the 1960s, the interest in program evaluation has grown as the US government expanded the social policies to fight the poverty under the Great Society programs. The federal spending was dramatically increased to support the Great Society program under Johnson administration; the rational budget allocation choice became crucial for the government. Those interventionist policy approach attracted people's attentions and they tried to know how it operated and what effects were given to them. In this context, the government became aware of the necessity of systematic analysis and evaluation method.

Apart from the US, from the early 1960s, many other countries including Europe started to adopt the concept of evaluation from the US (Ove Karlsson, 2003). In Europe, Sweden, Germany and the U.K. became the front-runners of evaluation development (Wollmann, 1986). In the UK, policy evaluation followed the similar pathway of the US. In the 1960s, Germany started to use the institutionalized program evaluation as a tool for the national management of governmental activities. Since then, the policy evaluation was used only for some specific areas. However, evaluation became popular after the reunification (1990), particularly related to assessment of East German institutions (Descy Op. cit.). In Sweden, in the mid-1960s, a systematic evaluation was seriously developed.

The second phase of evaluation development should be interpreted in the socio-economic context of the time. In the 1970s, the mentioned interventionist policies with various welfare programs were putting a strain on the government finances. Moreover, the oil crisis (1973, 1979) worsened the economic situation provoking the global economic recession and fiscal crisis. The retrenchment in the national budget and the cost saving were prioritized in policymaking as well as policy evaluation. In this context, the second wave of evaluation focused on cost-effectiveness. In the 1970s, this evaluation methodology was largely diffused in other countries as well[7] (Wollmann Op. cit.).

The third phase in evaluation arose in the 1990s based on the New Public Management (NPM). The NPM stemmed from market-oriented reforms in the 1980s mainly led by Anglo-Saxon countries like the Reagan administration and the Thatcher government. It aimed to have a small but efficient government in response to the government's failure to overcome economic recession and tax revolts problems (Gruening, 2001). During this period, many OECD countries adapted the NPM (Hood, 1995). The NPM was efficiency-focused and influenced by new institutional economics and managerialism, which aimed to install the private sector's management mechanisms in public sector (Hood, 1991). In the 1990's, the idea of NPM has formed evaluation as a tool mostly for the administrative management and control.

Like this, it is interesting to remark the increased demands in knowledge on the public decision stimulated the policy evaluation techniques. As seen, at its early stage, the evaluation was mainly based on the quantitative research methodology. However, the quantitative is not always the best solution to analyze obtained information. Evaluation is over time complemented by more qualitative research methodologies. Nowadays, several approaches are commonly in use in policy evaluation; a mix of qualitative and quantitative methods (Matt, et al., 2013).

4.3 Methods of policy evaluation

Policy evaluation aims to analyze the system that policy inputs (resources) transform into policy outputs (Vedung, 1997). There are various ways of categorizing policy evaluation methods.

First, policy evaluation can be divided into two types according to the time of application; ex-ante and ex-post (Wolpin, 2007). *Ex-ante policy evaluation* is the assessment of policy instrument before policy decision and formulation. This allows policymakers to predict possible consequences prior to policy implementation. On the other hand, e*x-post policy evaluation* occurs as the sequent process after policy implementation or before policy reformation (or termination). This approach is explained as a *summative evaluation;* evaluation is conducted to determine whether intended policy effects are achieved or not (Nachimas, Schuman). In addition, when some problems arise during policy implementation, *formative evaluation* can be conducted to find out better implementation strategies and methods to address the encountered issues. The procedure of policy evaluation varies depending on the purpose of use and policy method employed.

It is important to collect reliable data to increase the accuracy of policy evaluation; however, it is not always an easy task. The following shows two types of data collection methods.

- **Quantitative method** is an objective and empirical approach aiming at quantifying the problems using numeric data. This method has a structured and systematic way to collect data using statistic, mathematical or computational technique (Given, 2008). The method includes

[7] For example, in the Netherlands, the institutionalization of evaluation started in the mid-1970s with an attempt to link cutback management and budgetary review procedures.

experimental technique, standardized interview using empirical data, or modelling. It allows to easily comparing statistical data.

- **Qualitative method** is a subjective interpretation based on epistemological perspective (Guest, et al., 2013). This consists of words and observation, not figures. It requires in-depth understanding and interpretation to analysis the data. The representative examples are questionnaire survey, focus group interview, case studies, in-depth interviews, expert speeches, testimonials, observation and any published written materials like documents, reports and articles.

The qualitative provides a profound understanding about collected data, but the interpretation varies from researchers or the way of questions (Pawson and Tylley, 2001, p 109, Bernard Perret). The quantitative method is outstanding scientific approach widely used in engineering and sciences but has shortcomings because of the difficulties to determine the human activities, decision or politics that change over time (Quade, 1970). In this regard, the mix of both approaches can bring a complex research making up the weakness of both methods. Using this hybrid approach, researchers have broader access to data. The quality of data analysis depends on researchers' capabilities; harvesting survey data, data presentation, statistical analysis, causal relation investigation, and judgment technique.

The investigation of **causal relationship methods** is the heart of the evaluation but it is difficult to use. The policy system is complex and continuously interacts with many variables. Therefore, it is useful to use a simplified modeling of sub-system for a rigorous analysis of certain phenomenon. The simplest way is to compare results with and without such policies, ceteris paribus. In addition, **a logic map** can be used to conduct the appraisal process for new interventions based on a broader perspective; it helps visualize a systematic way of presenting the key steps required in order to turn a set of resources or inputs into activities that are designed to lead to a specific set of changes or outcomes (Hills, 2010) (See Part II chapter 2).

There are other techniques to judge the effectiveness and efficiency of policy; cost effectiveness analysis and cost-benefits analysis are commonly used.

Cost-effectiveness analysis is an assessment to find the most effective policy option among many alternatives to achieve the same objective. This technique is used for projects that have difficulties to monetarize the outcomes from the monetized inputs (e.g. one euro of costs). The multi-criteria analysis can be used to quantify the outcomes (Comunities and Local Government, 2009; Beria, et al., 2010; Popiolek, 2006).

However, **the cost-benefits analysis** is appraisal technique to find the best policy option by comparing the total expected cost of each option against the total expected benefits (Comunities and Local Government, 2009). Unlike the cost-effectiveness analysis, this method requires to monetarize the benefits and costs based on the time value of money. Its main barriers are difficulties related to monetary valuation of impacts of all alternatives. Benefit/Cost ratio is commonly used techniques.

The **modeling** is an alternative method of sample experimental technique. In economy, the econometrics linear model is often used to study macro-economic data. The goal is to find the coefficient for each input data that explains results. The modelling gives a good result only when the model is well designed with strong theoretical arguments.

4.4 Evaluation of renewable energy policies

This section concerns the evaluation of renewable energy policies. The success of public policies is determined by how well they satisfy the targeted objectives (cf. 3.4.2). Renewable energy policies often aim to increase the installed capacity of renewable energy technologies as well as the power generation from them. It is also important to define the policy target to conduct evaluation process because the policy target is the reference for the whole process of evaluation.

Policies should be evaluated on a regular basis, in particularly when the financial support is involved. Literatures use various criteria to evaluate renewable energies policies ((IPCC, 2011b; IRENA, 2012b; European Commission, 2010; Bohm & Russel, 1985). The common criteria that most literatures take to evaluate renewable energy policies are captured as below.

- **Effectiveness**: To what extent, were the intended objectives met? This attempts to assess the outcomes from renewable energy policies. For example, the actual increase in installed capacity (MW) or electricity output (MWh) within the specified time period can be measured; both absolute and percentage (e.g. growth rate) terms can be used (IRENA, 2014b). The appraisal of technological or geographical diversity is important indicator for long-term sustained growth of renewable energy technologies (IPCC, 2011a).
- **Efficiency**: The ratio of outcomes to inputs (IRENA Op. cit.); how economically were targets of renewable energies achieved against the economic resources spent (cost-effectiveness). The financial terms or social costs/ impacts can be used; e.g. expenditure for each unit of installed capacity ($/MW) or electricity outputs ($/MWh).
- **Equity**: IPCC report defines equity is the incidence and distributional consequences of a policy, including dimensions such as fairness, justice and respect for the rights of indigenous people (IPCC Op. cit.). This can be appraised by observing the distribution of costs and benefits of a policy; e.g. changes in family spending in terms of electricity fares with increased renewable energies. The fairness of policy is important concept; the policy costs should be fairly allocated among stakeholders concerned. The polluters pay principle is usually considered to be fair (IPCC Op. cit.).
- **Institutional feasibility**: To what extent, does a policy instrument is likely to be viewed as legitimate, gain acceptance, and be adopted and implemented (IPCC Op. cit.). This assesses how well policy elements fit with the social institutions or their institutional capacities. The criterion explains the difference between theoretical policy design and policy realities. For the successful policy implementation, the wide acceptance of stakeholders is required. This also explains the reason behind the good and bad policy practices. Case studies can be conducted to identify success or failure factors.

Other criteria are also studies in literatures (OECD, IRENA). For example, IRENA uses **replicability** to examine how well a successful policy can be reproduced by another country (IRENA, 2012b). This gives opportunities to define critical factor that leads to successful policy implementation by comparing different policy results under different policy context or conditions. In addition, **consistency** appraise if other external (related) policies do not contradict to concerned policies (van Reisen, 2007). **Coherence (or relevance)** assesses the appropriateness of a policy if it really addresses the matter concerned (OECD, 2012).

Among them, **effectiveness and efficiency** are the most commonly used standards to determine the success of policy instruments (IPCC Op. cit.). In this study, these two criteria are mainly considered.

5 Conclusions

This chapter showed the necessity of public policy in support of PV energy. Energy is a vital need for human life and economic activity, and thus directly associated with national security and socio-economic development. Government's intervention in the energy sector has always been playing an important role in setting market rules and the national focuses on energy policy vary according to the ruling ideology.

In the context of energy transition renewable energies are highlighted as a solution but they are insufficiently attractive to private investors. In addition, each government has a different policy focus among three pillars (energy security, energy equity and environmental sustainability) according to the national strategies. The policy decision of each government also varies according to the policy context and its historicity. Public policies in favor of solar PV energy should be explained in this context. Therefore, it is important to take the policy context that evolves with time (dynamics features) into account for the PV policy analysis.

An innovation policy is thus needed to improve the position of PV technologies in the energy system because it requires integration efforts that accompany organizational, institutional and practical changes. The innovation policy includes supply-side policy (R & D, innovation in industry) and demand-side policy. Therefore, in this context, different policy instruments of both the supply and demand side were presented. In addition, the experience curve was presented; this is a simple and useful tool to discuss the progress of PV technologies and forecast it. This method will be used in Part III to give a brief idea of PV costs in the future.

After recalling the context of public policy in support of renewables including PV, a historical evolution of public policy evaluation and various methodologies were presented. We concluded that a 'logic model' is a useful tool to visualize a systematic way of presenting the key steps required in order to turn a set of resources or inputs into activities that are designed to lead to a specific set of changes or outcomes. Our research will be based on this approach to construct a schematic map of PV policy mechanisms, a tool for a retrospective study in Part II. In addition, we will attempt to define the causal relationship among variables of the PV policy mechanisms. Furthermore, the thesis will take the most used criteria to evaluate public policies in support of renewable energies; efficiency (ratio of inputs to outcomes) and effectiveness (ratio of outcomes to objectives) of public policies.

Chapter 2. PV technologies, PV usages and PV integration in energy system

In this chapter, we discuss on PV technologies, PV usages and PV integration.

First, section 1 presents the state of the art analysis of PV technologies with their costs in the electricity system. A general perception of the PV value chain is first presented from PV cells to the complete system. It also summarizes different PV technologies with their development stage. In this section, we mainly focus on silicon technology that dominates the current market and locks the emergence of other technologies. It is then followed by further discussion on the complete PV system, in which other issues were raised such as soft costs. To complete the analysis of the PV system, a particular zoom on the storage of electricity is done; this is important to address the issue related to intermittency of PV electricity production. We take a special attention to the lithium Ion (Li-ion) battery. It is the most developed technology with the potential cost reduction by economies of scale in the short-term period. It can be directly associated with the decentralized PV systems. Therefore, it gives potential opportunities for large deployment of PV systems in the future.

Once PV technology is defined, section 2 analyses PV usages (off-grid and grid-connected: centralized and distributed), using the SWOT analysis method. The methodology of SWOT (Strengthens, Weakness, Opportunities and Threats) analysis is commonly used in business to define the most effective strategies for business decision makers. It helps identify strong and weak points of internal resources and external environmental factors like opportunities and threats that can be faced in the marketplace. The same objective exists in terms of public policy because the policymaker seeks to adopt the most effective strategy to maximize the benefits from public investments. In this regard, the SWOT method is used to define the best development strategies for each PV application for policymakers. The study concludes with a reflection on the possible future PV usages (coupling) in the energy sector.

Section 3 addresses the impact of large scale PV integration in electric power system. There are many critical issues related to the intermittency of PV electricity production. To understand these issues well, section 3 presents the specificities of the electricity market and electricity supply-demand management. This study then brings to the question related to the systemic costs of PV. It attempts to define the main impacts that should be taken into account by policymakers.

1 The state of the art analysis of PV technology systems

This chapter aims to give a brief review on solar PV technologies. The current market is dominated by silicon technology. Accordingly, this chapter gives a close look at the value chain of this technology; this is useful process to understand the PV industry. Then, all existing technologies are also presented with the specification, the level of maturity and the constraints and opportunities for development.

1.1 Solar PV value chain

The PV panel is an assembly of modules. For the most common wafer-based crystalline silicon PV system (c-Si), the cell is the basic photovoltaic unit and the module is a connected assembly of cells. PV system employs solar panels to produce electricity. The installed PV system is connected to utility grid or has a stand-alone power system type (off-the-grid system). A PV system (**Figure 7**) is composed of solar panels (arrays) and all the hardware that makes the system functional.

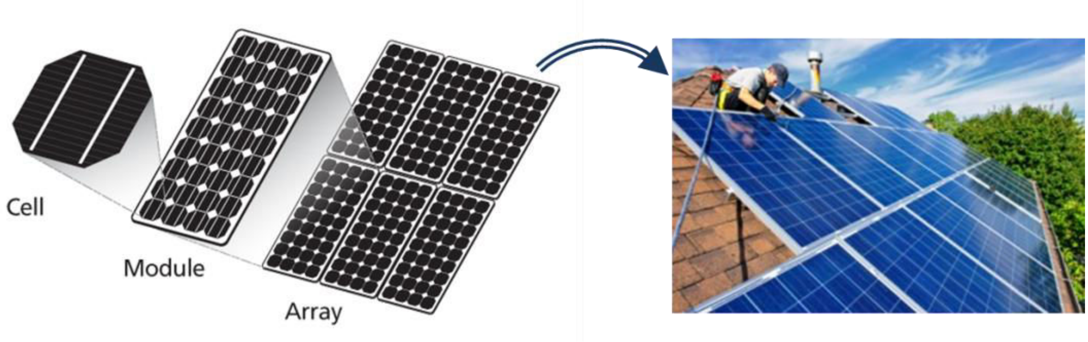


Figure 7: PV cell, module and rooftop system

The manufacturing process of wafer-based silicon PV modules is comprised of four steps (IEA-ETSAP and IRENA, 2013);

- Production of the PV grade semiconducting material: high-skilled technology
- Production of ingots/wafers
- Production of PV cells: somewhat sophisticated manufacturing
- Assembling of PV modules: labor-intensive process

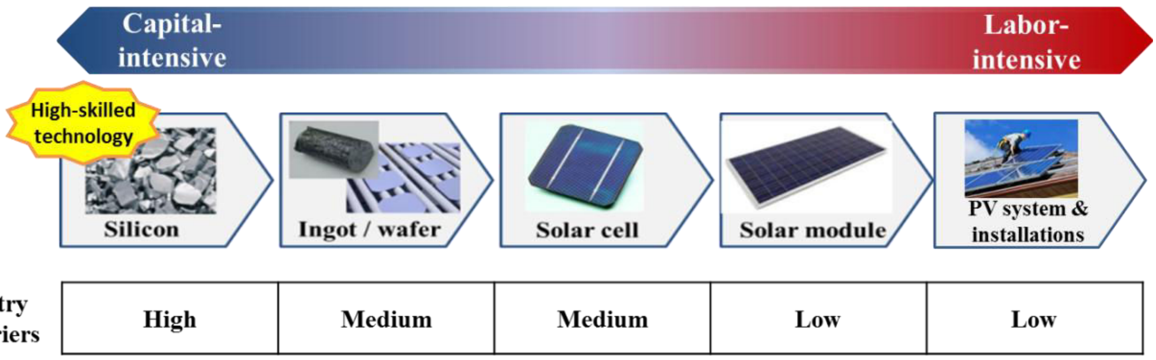


Figure 8: C-Si PV value chain (IEA-ETSAP and IRENA, 2013)

The silicon is a very common material on earth. However, the silicon needs to be very pure to become 'solar-grade silicon', and the process to obtain it is quite cumbersome and requires the high skill (IEA-ETSAP and IRENA Op. cit.). A crystal (mono-crystal or poly-crystal) of silicon is created with the high purity silicon feedstock. The silicon is melted in ingot to get the shape of the cell and the ingot is cut in thin layer to obtain wafers. The solar cell is created based on this wafer.

As **Figure 8** shows, PV upstream market is more capital-intensive while the downstream is more labor-intensive. In addition, the PV industry gives highest profits for upstream sector (e.g. silicon making) because it has a very high entrance level compared with downstream areas.

1.2 Solar PV cell technology (crystalline, thin film, and other technologies)

Solar photovoltaic (PV) cells convert sunlight into electricity using the photovoltaic effect. There is the wide variety of materials capable of producing the photovoltaic effect (Gangopadhyay, et al., 2013). Over the last decades, PV technology has been constantly improving performance and reducing costs (IEA-ETSAP and IRENA Op. cit.). They can be clarified into three groups depending on materials used and maturity of commercialization.

- **Crystalline silicon technologies** : mono-crystalline (mono-Si), multi-crystalline (multi- Si)
- **Thin film PV technologies**: amorphous (a-Si), micro morph silicon (a-Si/a-Si/µc-Si), Cadmium-Telluride (CdTe), Copper-Indium-Selenide (CIS) and Copper-Indium-Gallium-Diselenide (CIGS)
- **Other technologies**: concentration PV (CPV), organic PV, dye sensitized PV, and perovskite, etc.

The most mature technology is silicon-based technologies. Historically, the PV technology used silicon wafer, which is a thin slice of silicon crystal (semiconductor material). The solar cell is built based on this unit and then assembled in a module. It is the *wafer-based crystalline technology* (**c-Si**).

Another way to build a PV cell is to deposit a thin layer of photosensitive material on a neutral materials or a substrate instead of a solid silicon bloc. It is the thin-film technology. It was developed first on silicon material (amorphous silicon **a-Si**). Just after, efficient but non-silicon materials emerged; e.g. cadmium-telluride **CdTe**, copper-indium-selenide **CIS**, and copper-indium-gallium-diselenide **CIGS**.

Other technologies exist; the most mature technology among them is the concentrated photovoltaic (**CPV**) system. It uses an assembly of high efficient multi-junction solar cells with lens that concentrate the sunlight. The concentration of the sunlight allows a higher efficiency of the cell. There are other pre-commercialized technologies; e.g. Dye-sensitized solar cells (**DSSC**), Organic PV cells (**OPV**) and **emerging** solar cells like perovskite cells.

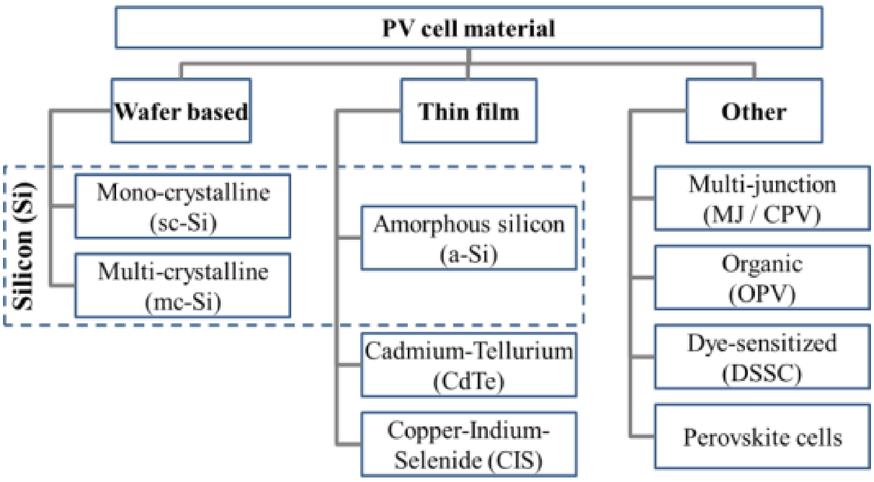


Figure 9: PV cell technologies (IRENA, 29-30 May 2014)

Like this, different semiconducting materials are responsive to different energy levels and wavelengths of light, with different level of efficiency and with more or less complex fabrication process. In this regard, it is worth reviewing the characteristics of each technology to define opportunities and threat factors of each technology.

The following **Figure 10** shows solar cell R&D efficiency gain of main technologies over the last decades (Fraunhofer ISE, 2014). A more complete graphic for all the existing technologies is provided by NREL on its website (NREL website); there is a significant progress of efficiency of emerging technologies.

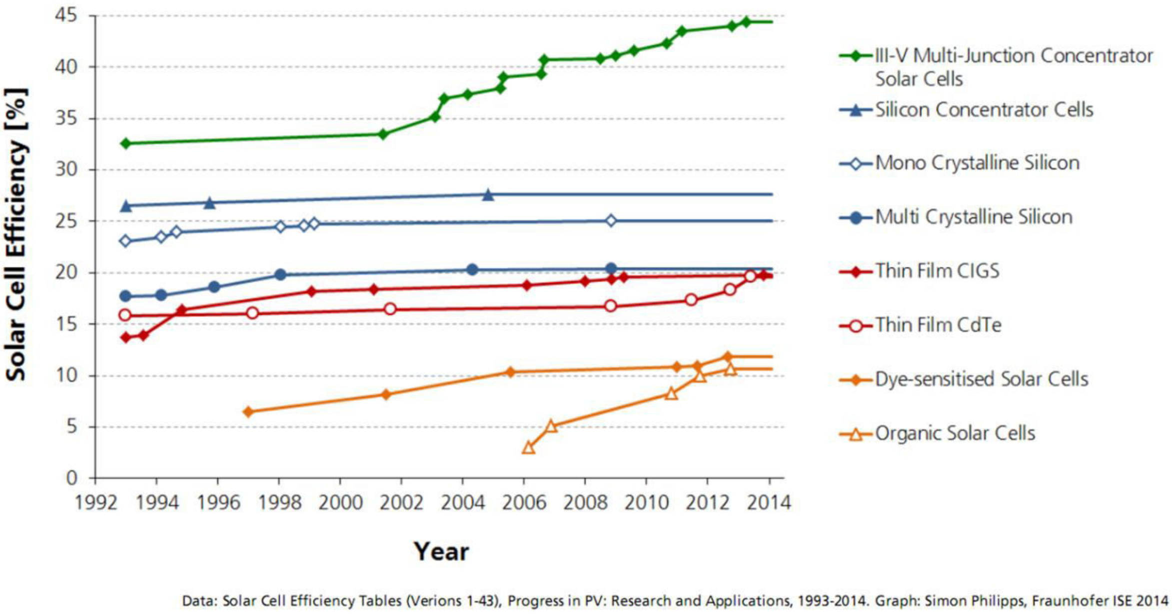


Figure 10: Overview of solar PV technology efficiency gain (R&D)

The economic criteria are important drivers for technology choice. Table III summarizes important features of different commercialized technologies.

		Crystalline silicon[8]		Thin film[8]		
		mc-si (mono)	pc-si (multi)	a-Si / µc -Si	CdTe	CIGS
History		Since 1960s		Since 1970s	Since 1980s	Recently commercialized
Market share (IEA 2014)[9][10]		90%		10%		
				3%	6%	1%
Efficiency	**Best R&D cell**[11]	25%	20.4%	13.4%	21%	21.7%
	Best R&D module	22.9%	18.5%	10.9%	16.1%	15.7%
	Commercial module[12]	14-20%	13-15%	6-9%	9-11%	10-12%
Best costs of module production [13] (€/Wp)		0.6-0.7		0.5	0.4-0.5	0.6-0.7
Installed PV system costs ($/Wp)			2.74	2.71	2.27	2.93
Life time[13]		25 (30)	25 (30)	25	25	25
Area needed per kw (for modules)[14]		~ 6 m^2	~ 7 m^2	~15 m^2	~10 m^2	~9 m^2
Power temperatures coefficient (%/k)		-0.40	-0.45	-0.25	-0.25	-0.31
Weak point		Cost		Low efficiency	Environmental concerns (Cd toxicity)	Most complex production process (high production costs)
Opportunities		Efficiency		Low production costs Easy integration into the façade Lower temp coefficient	Simple and quick manufacturing Cheapest PV technology	

Table III: Features of different commercialized cells technologies

Table IV presents important features of different emerging technologies:

		CPV		Emerging PV[15]		
		LCPV	HCPV[16]	Dye-sensitive	Perovskite	Organic
Market share (IEA 2014)[17]		Less than 1%				
Efficiency	**Best R&D cell**[18]		**44.7%**	**11.9 %**	**20.1%**	**11.1%**
	Best R&D module		36.7%	-	-	6-8%[19]
	Commercial module		~30%	-	-	4-5%
Installed system costs ($/Wp)			3.1	-	-	-
Life time			25[20]	>10 years	> 1 year[21]	-
Area needed per kW (for modules)[22]			~3.5 m^2	~ 10 m^2		
Power temperatures coefficient (%/k)			-0.04[23]			
Weak point		Cost Tracking system is needed		R&D stage (stability issue)		
Opportunities		Land usage Adapted to high insolation area (sunbelt)[24]		Cost Flexible	Efficiency Cost	Cost Flexible

Table IV: Features of different emerging technologies

8 (Fraunhofer ISE, 2014; Shahan, 2013)
9 Market share 2013 (IEA, 2014)
10 Thin film technology market share (2013) (NPD Solarbuzz, 2013, p. 10)
11 (NREL website)
12 (IEA, 2014)
13 (IEA-ETSAP and IRENA, 2013, p. 24)
14 Author's calculation based on 1000 kWh insolation.
15 (Shahan, 2013; NREL, 2012)
16 (Fraunhofer ISE, 2014)
17 (IEA, 2014)
18 (NREL website)
19 (IRENA, 2012)
20 (Fraunhofer, 2014b)
21 (Meza, 2015)
22 (IEA-ETSAP and IRENA, 2013)
23 (Antonini, et al., 2014)
24 (IEA, 2014)

1.3 Market lock-in situation by c-Si technology

As seen there are various technology choice in term of PV power, however, the current PV market is locked in by c-Si technology (IEA 2014, Taillant 2002, Finon 2008, 2011).

Historically, along with the technological advancement of silicon translators, crystalline silicon technology was favored with the possibility for PV manufacturing firms to purchase unwanted silicon from the semiconductor industry and became the dominant technology in the PV market. However, the increasing demand on high-purified silicon from the flat screen sector, the silicon supply is not any more abundant raw materials and there were silicon shortage problems in the mid-2000s.

Over the last years, the rapid increase of c-Si cell and module production based on economies of scale, largely reduced the world's PV modules prices and further increased the economic advantages of PV systems based on c-Si technology; it now accounts for around 90% of the market values (technological lock-in, Finon 2008).

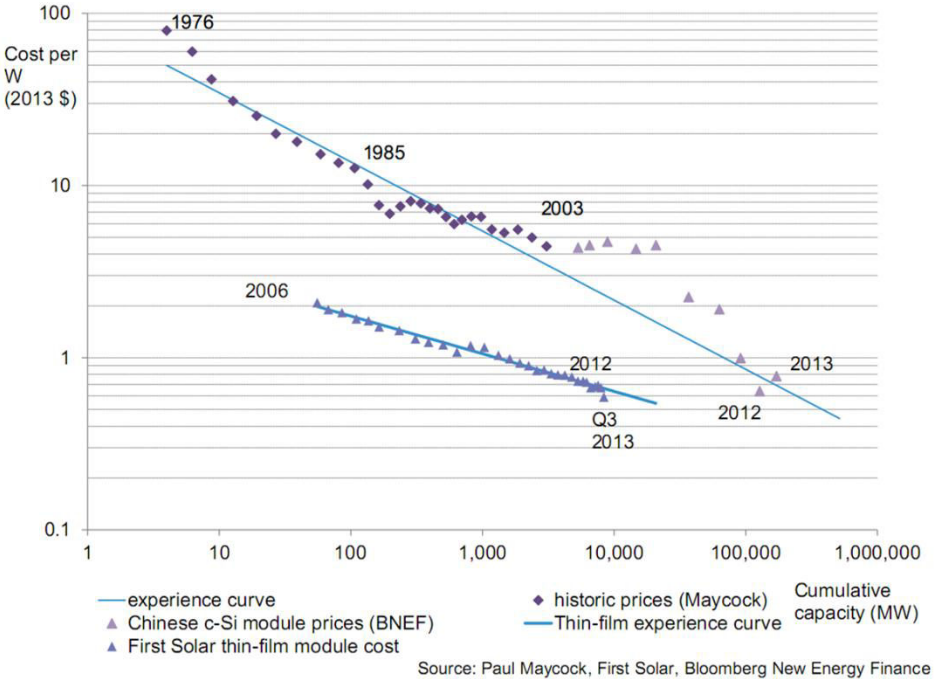


Figure 11: Learning curve (or experience curve)[25] for c-Si technologies and thin film technologies (Bloomberg New Energy Finance, 2014b)

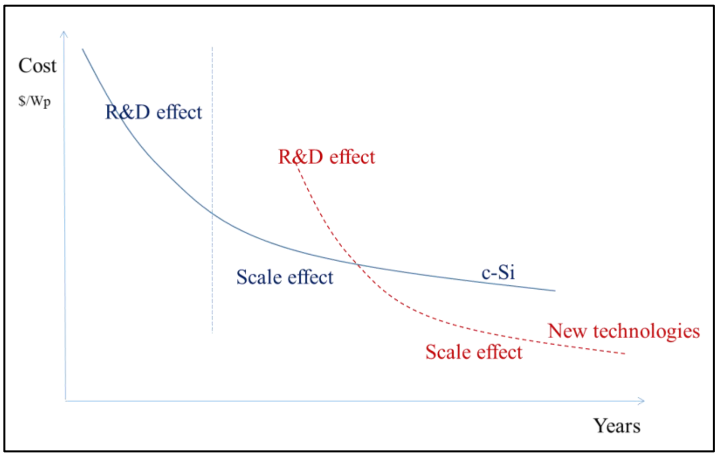


Figure 12: PV technology breakthrough

[25] See chapter 1 section 3.2

On the other hands, in spite of a lower efficiency, thin film PV technologies have advantages compared to crystalline silicon technologies; for example, low manufacturing costs (CdTe), low production cost and better yield (a-Si), more appropriate usages of building integration (transparent thin films..). These advantages give new ideas of diverse opportunities for PV growth. Furthermore, the hybrid option of PV technology can enhance the advantages of PV technologies.

However, the established market has fewer incentives to make a long-term investment in those technologies because of the higher risks and economic competitiveness even though they are more suitable in certain areas. Those new technologies have a commercialization barrier competing with mature technologies despite its advantages. In this regard, there is a need for public policy to explore new growth opportunities.

1.4 Solar PV system (focus on non-module sector)

1.4.1 Breakdown of non-module parts of PV system

The PV system is ready-to-use. Therefore, the costs of PV system include PV modules, auxiliary parts (non-module hardware) and soft costs. The costs for non-module hardware and soft costs are called ‘balance of Systems (BOS) costs’.

The non-module hardware includes the supporting parts to mount modules (e.g. racking), the inverter to converts the direct current (DC) power from the cells to alternating current (AC) power to be compatible with the electrical network, and other electrical devices (e.g. power control system, switchgear, fuses, cabling). In addition, the PV system can couple with energy storage system (e.g. battery). The usage of a battery is necessary for off-grid PV systems.[26]

Soft costs cover any other services needed to design, install, and connect the PV systems to the network. The following indicates detailed items of soft costs.

- The costumer acquisition cost
- The engineering cost
- The installation cost
- The permitting, inspection and interconnection costs (PII)
- The profit and overhead of all the companies involved in the process

For a residential system, the soft costs represent around 50% of the total investment in 2014. Persistent efforts are ongoing to make non-module hardware devices more reliable, to reduce their cost and extend the lifetime to keep pace with that of the module (IPCC).

- Module : ~40% of PV system price
- Non-module hardware: ~10% of PV system price (e.g. inverters, cables, batteries, fixed supports)
- Soft costs: ~50% of PV system price (e.g. engineering, customer acquisition, installation, profit and overhead costs, and permission, inspection and interconnection (PII))

[26] (IEA-ETSAP and IRENA, 2013)

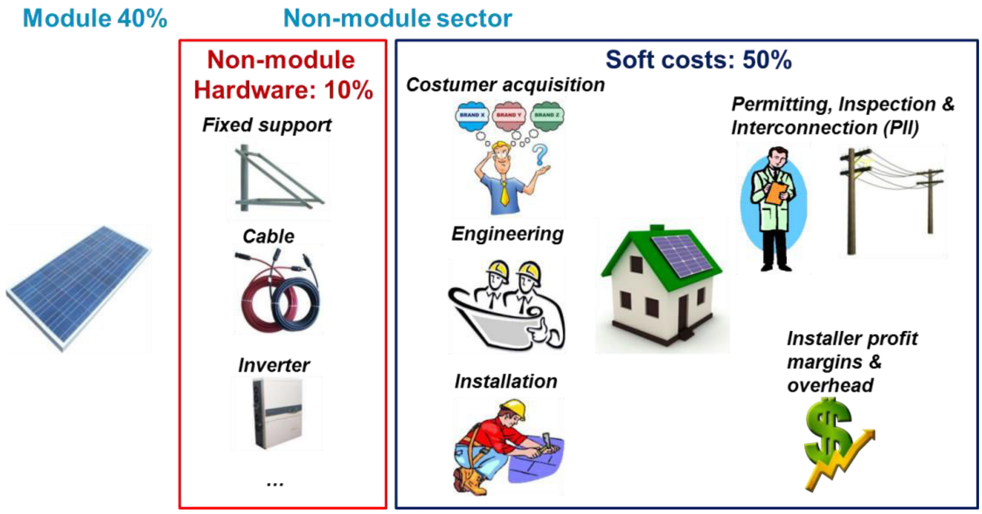
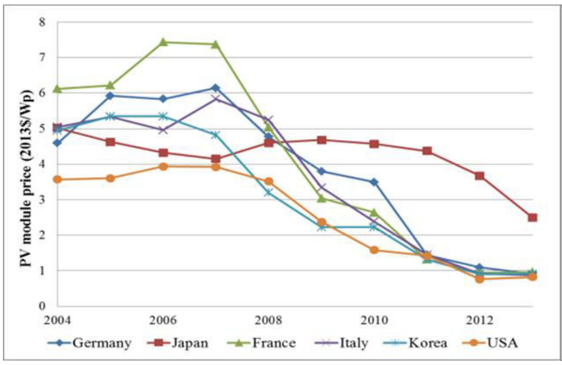


Figure 13: Components of the residential PV system costs (Seel, et al., 2014; ADEME, 2012)

1.4.2 Solar PV price trend: increasing importance of non-module sector

The PV system price is a key variable of the initial investment when calculating PV electricity costs. Until recently, the reduced module prices were the most focused driver to enhance the economic competitiveness of PV electricity. Research and industry have striven to decrease module production unit costs through cell efficiency improvement and economies of scale. Over the last decade, the PV system price drop was mainly correlated with the module price reduction. However, it seems difficult to expect the future PV system price to reduce by means of module price drops alone, as we have seen with historical data. Other factors became more important such as soft costs.



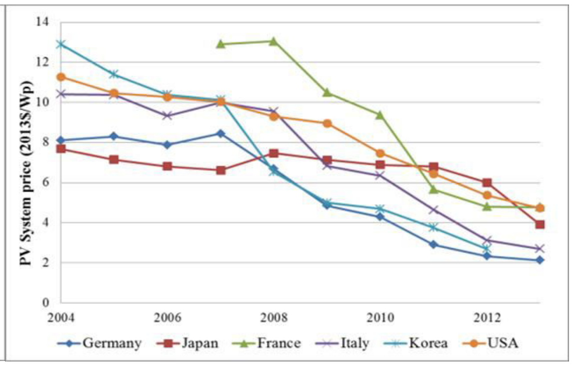


Figure 14 (left): Change over time in PV module prices[27]
Figure 15 (right): Change over time in residential rooftop system prices [27]

As **Figure 14** shows, the average selling prices of PV modules are currently almost the same in many countries; the global module price is now less than $1/Wp. However, there are differences in PV system prices depending on the country (see **Figure 15**). The current economic competitiveness of PV

[27] (IEA PVPS, 2002 to 2014; IEA PVPS France, 2002, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014; IEA PVPS Germany, 2002 to 2014; IEA PVPS Japan, 2002 to 2012; IEA PVPS Italy, 2002, 2003, 2006, 2007, 2008, 2009, 2011, 2012, 2013)

systems needs to be discussed in a comprehensive manner by taking into account other **accompanying costs** involved in producing PV electricity.

The current differences in PV system prices are mainly due to non-module prices. Therefore, the improvement of PV system competitiveness can be delivered by improving them. A well-designed policy can be a trigger to boost such price reductions.

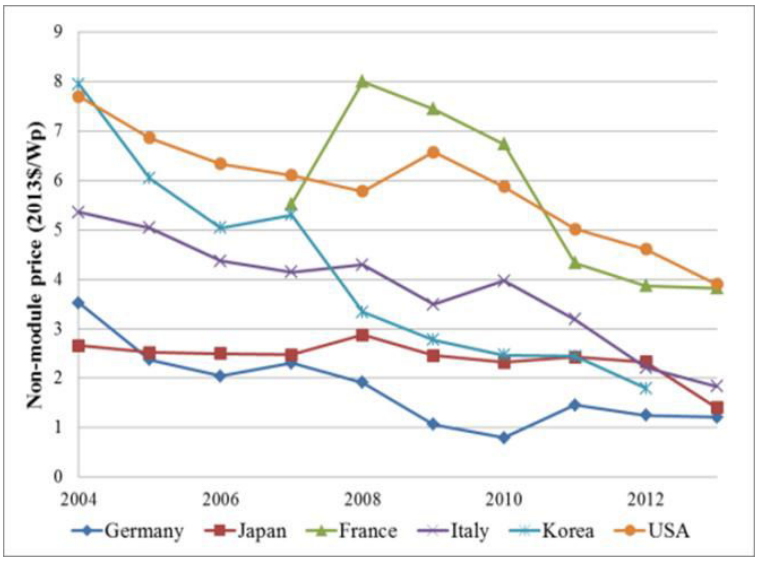


Figure 16: Change over time of the non-module price (system price – module price)[27]

1.4.3 Non module costs and country market sizes

The global PV module market now takes advantage of the cumulative knowledge stock and experience, thereby sharing a similar price. The positive correlation between the module price drop and the size of cumulative installations has been demonstrated in many studies, reflecting the PV module's learning rate of around 20%, which means that each time the cumulative installed capacity doubled, the price went down by 20% (Kersten, et al., 2011).

It is now worth reviewing a possible correlation between the cumulative installed capacity of PV systems and the reduction of non-module costs.

We aim to review the variation in non-module prices within the PV system price using the learning-curve concept. The mathematical model is described in equations (1) and (2).

$$C_t = C_0 \times \left(\frac{X_t}{X_0}\right)^{-b} \qquad (1)$$

$$LR = 1 - 2^{-b} \qquad (2)$$

With:

C_t: Cost at time t, X_t: Cumulative installed capacity at time t

C_0 : Reference cost, X_0 : Reference cumulative installed capacity

b: Coefficient to find, LR : The learning rate

The graph compares empirical data of non-module prices with cumulative installations in several countries, in order to provide insight into a possible correlation between them.

Data on the annual installation growth and non-module prices were taken from 1993 to 2013 whenever available. Six countries were considered; they accounted for 61% of the global cumulative installations in 2013 having a continuous installation policy over several years (IEA PVPS, 2014).

The curve focuses on residential rooftop PV systems for which the non-module costs account for highest fraction.

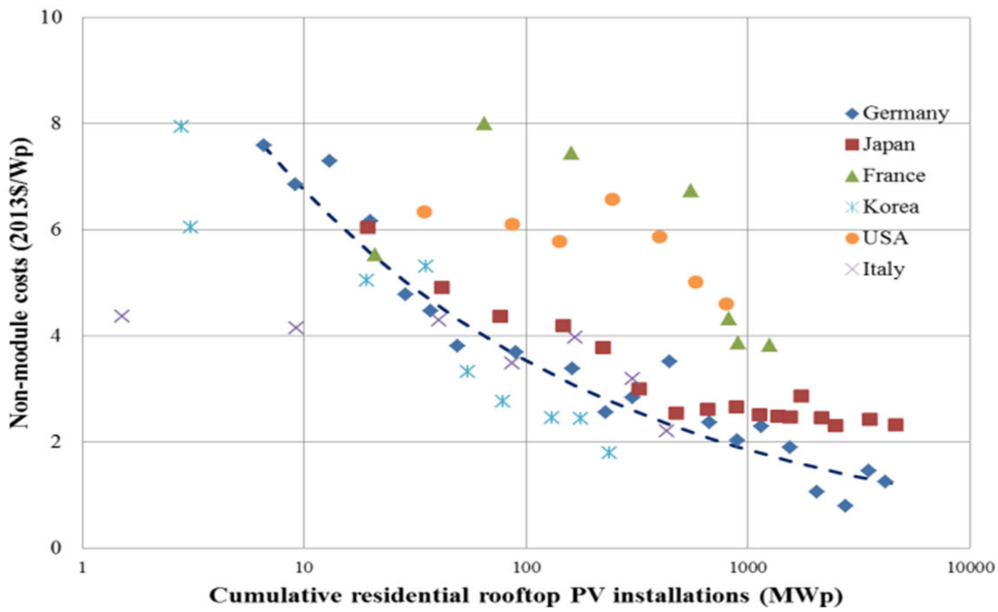


Figure 17: Learning curve for non-module costs of PV rooftop systems in different countries[28].

Fig. 4 shows that each country has its own learning curve; they can be split into two groups;

1. Italy, Germany, Korea and Japan share a similar slope
2. France and the US have a different slope.

Even though there are some country-based differences in terms of the learning rate, it seems proven that there is a positive correlation between the cumulative installations and the non-module price drops.

Germany has a learning rate of 17.6% and its learning curve equation is described in (3)[29]:

$$C_t = 7.6 \times \left(\frac{X_t}{6.6}\right)^{-0.28} \qquad (3)$$

The learning rate is almost the same for all countries in the first group. The difference between them is low and stays constant. This could be due to irreducible costs like different consumer prices or taxes.

It would be worth analyzing countries' different costs to understand difference factors, and thus to amend strategies to increase the economic competitiveness of PV systems.

[28] (Bundesministeriums für Umwelt, Natur-schutz und Reaktorsicherheit, 2011; Bundesministeriums für Wirtschaft und Energie, 2014; Gestore Servizi Energetici, 2014; Barbose, et al., 2013; IEA PVPS Japan, 2012; James, et al., 2013; IEA PVPS Korea, 2012; ADEME, 2012; Lesourd & Park, 2005)

[29] Author's calculation, 1993 data were used for C_0 and X_0.

1.5 Electrical energy storage

1.5.1 Importance of energy storage for intermittent PV power

The PV energy is an intermittent renewable energy source. Large-scale integration of PV power in the electric system poses challenges like electricity supply and demand balancing. ***Energy storage systems*** store energy for a certain period of time before releasing it to supply energy when needed (IEA, Mar. 19, 2014). They allow storing the electrical energy when PV output is high and the demand (or price) low. The stored power is generated when PV output is low and the demand (or price) high. By using this solution, the curtailment of PV energy is reduced and PV system operates more efficiently with increased flexibility. In addition, it also reduces transmission congestion and increase the reliability of the electric system (CEA, Oct. 18, 2012). Moreover, the storage system is compulsory for PV off-grid system to increase its efficiency.

The choice of storage depends upon the situation of its electric system (e.g. generation mix, demand profile, or connectivity to other electric power systems) (Tuohy & O'Malley, 2011). The electricity storage systems compete with other alternatives such as interconnection with other electric power systems, flexible generation or demand-side actions. The economic aspects of storage systems will influence such choice. Many energy storage systems exist; some technologies (e.g. pumped hydro storage) are mature but most are still in the early stages of development and not yet economically viable. The high capital costs of storage system and its inefficiency in operation hinder their large-scale deployment. Additional efforts are needed to further develop energy storage system. It will help to integrate a high level of PV power in the electric systems.

In this regard, in the next section, it attempts to study the main energy storage technologies with a focus on the battery systems that can be easily coupled with the PV system. When their costs decline, it would be much easier to use PV systems in the current and future electric systems.

1.5.2 Electricity storage technologies

The electricity storage is an extensive field with numerous solutions. However, only few technologies are commercialized. The most mature technology is the Pumped Storage Hydropower (PSH). It is a hydroelectric energy storage system useful for load balancing. It operates on the same principle of conventional hydroelectric power plants; this technology pumps water from a lower reservoir up to an upper reservoir to store the energy and the stored water is released through turbines to produce electricity. Since the le 1920's, PSH has been playing a key role for large-scale electrical energy storage solution (IPCC ch8). PSH represents 99% of installed energy storage capacity with about 140 GW in electricity grids in the world (IEA, Mar. 19, 2014). However, it has geographical constraints which require an upper reservoir; accordingly, it is more feasible in mountainous regions.

The remaining 1% is a mix of various technologies, which are under development; e.g. compressed air energy storage (CAES), sodium-sulphur (NaS) batteries, lithium-ion batteries, lead-acid batteries, nickel-cadmium, flywheel, hydrogen storage and redox-flow (IEA).

Table V summarizes energy storage technologies; there are three groups of electricity storage systems according to the provided services: short- and long-term storage and distributed battery storage. In general, apart from PSH, CAES, and some battery technologies, most technologies are currently at much earlier stages of development.

Electricity storage systems	Technologies examples	Benefits	Limits
Short-term (seconds-minutes) storage applications	Supercapacitors and SMES[30] technologies Flywheels	Address short bursts of electricity into the energy system	High costs
Long-term (hours-seasons) storage applications	Pumped-storage hydropower (PSH), Compressed air energy storage (CAES) Hydrogen storage	Global solution for bulk (large-scale) storage Opportunity to increase storage capabilities	High upfront investment costs Geographic requirements High capital costs
Distributed battery storage	Lithium-ion batteries, Sodium-sulphur (NaS) batteries, Lead-acid batteries,	Use for both short- and long-term applications Small-scale storage but highly scalable and efficient	Energy density, power performance, lifetime, charging capabilities, and costs

Table V: Electricity storage technologies (IEA, Mar. 19, 2014; CEA, Oct. 18, 2012)

The electricity storage concerns the entire electric system. The electricity storage systems can be deployed in different locations of electric power system across electricity supply, transmission and distribution (T&D), and electricity demand (end-users). Table VI demonstrates diverse storage technologies applied in each sector across the electric power system with varying capacity. Batteries and hydrogen storage can be used in both supply and demand aspects. While batteries are applied for distributed and off-grid storage systems or short-term storage, hydrogen can be used for long-term storage.

	Capacity	Technologies
Supply	Greater than 100MW	PSH, CAES, Batteries, and Chemical- hydrogen storage
T&D	From 10kW to 100MW	Flywheels, Supercapacitors, and Superconducting magnetic energy storage (SMES)
Demand	Less than 10kW	Batteries, Chemical- hydrogen storage

Table VI: Storage technologies applied in each sector across the electric power system

As seen, the high costs of electricity storage technology are the main barrier for the large deployment of systems. The enhanced economic feasibility of storage system is essential for a large-scale commercialization. Active research is ongoing to improve the system efficiency, to extend the lifetime, and to reduce the costs.

Table VII gives the economic features of different storage solutions (enea consulting, 2012; CEA, Oct. 18, 2012; U.S. Department of Energy, 2013) . We can see that most technologies still have rooms to improve their economic aspects to be deployed on a commercial scale.

[30] Superconducting Magnetic Energy Storage

Technology	Maturity	Yield (%)	Lifetime (years)	Investment ($/kW)
STEP	Deployed	0.65-0.80	50.00	1000
CAES in cave	R&D	0.5	35.00	550
CAES with tank	Deployed	0.5	35.00	600
Synthetic Natural gas	R&D	-	-	-
Flywheel	Demonstration	0.85-0.95	20.00	1500
Hydrogen	R&D	0.25-0.35	10.00	6000
Pb battery	Deployed	0.7	11.00	300
Li-ion battery	Deployed	0.7-0.75	12.50	1000
Battery NaS	Demonstration	0.7-0.75	12.50	1250
Redox-flow battery	Demonstration	0.65-0.75	17.50	2000
SMES	Demonstration	0.75-0.80	25.00	250
Super capacitor	Demonstration	0.9-0.95	12.50	250

Table VII: Economic features of different storage solutions

In conclusion, electricity storage systems are the important element to decarbonize the future electric power system. The optimal choice of energy storage will depends on the current condition of energy system and future development aspects. However, as seen, the high costs of storage are an obstacle to solve; persistent R&D activities under targeted supports are needed to achieve a cost reduction. In doing so, it would increase energy access using PV system (off-grid or distributed PV system coupled with batteries). Furthermore, the storage system can be integrated in grid-connected PV system for smoothing demand peaks and backup power for PV systems. Moreover, combined with the transport sector, the enhanced batteries help diversify the transportation fuel resources.

1.5.3 Price perspectives of Lithium ion (Li-ion) battery

Lithium ion (Li-ion) battery is the most developed technologies with potential cost reduction by economies of scale in the short-term period. It can be directly associated with PV systems, in particular with distributed PV systems. Therefore, even though many other promising technologies exist, the analysis with Li-Ion technologies gives a basic scenario. It allows us to define the potential opportunities for the large deployment of PV systems coupled with battery in the future. Therefore, in our study, the price perspective of Li-ion battery is studied.

Along with the development of the mobile devices (e.g. smartphone, notebook, etc.), Li-ion battery demonstrated a remarkable evolution over the past 25 years, reducing its volume and price. The battery development is still driven by increasing demand in mobile devices but also by the emerging markets like Electrical Vehicles (EV).

The required capacity of battery for residential usage and electric vehicle is quite similar. The residential PV system with battery thus benefits from the development of electrical vehicles. For example, Tesla, the electric carmaker, proposed a battery system for residential usage in 2015; the price of Tesla's Powerwall is $ 3500 for a 10 kWh and $ 3000 for 7 kWh (Tesla motor). If the installation cost is included, the Deutsche Bank estimated the cost of the battery at 500 $/kWh (TECSOL, 2015). According to the Deutsche Bank's report, Telsa's price will be reduced by 57% to $ 150/kWh in 2017 and by 71% to $ 100/kWh in 2024 (Deutsche Bank, 2015).

The Japan EV roadmap aims to reduce the battery price to 270$/kWh in 2020 and 130$/kWh in 2030 (The committee on climate change, 2012). Furthermore, Mc Kinsey & Company expected the price of Li-ion battery packs achieve at 197$/kWh in 2020 and 163$/kWh in 2025 (Hensley, et al., 2012). **Figure 18** displays different projections of the Li-ion battery prices.

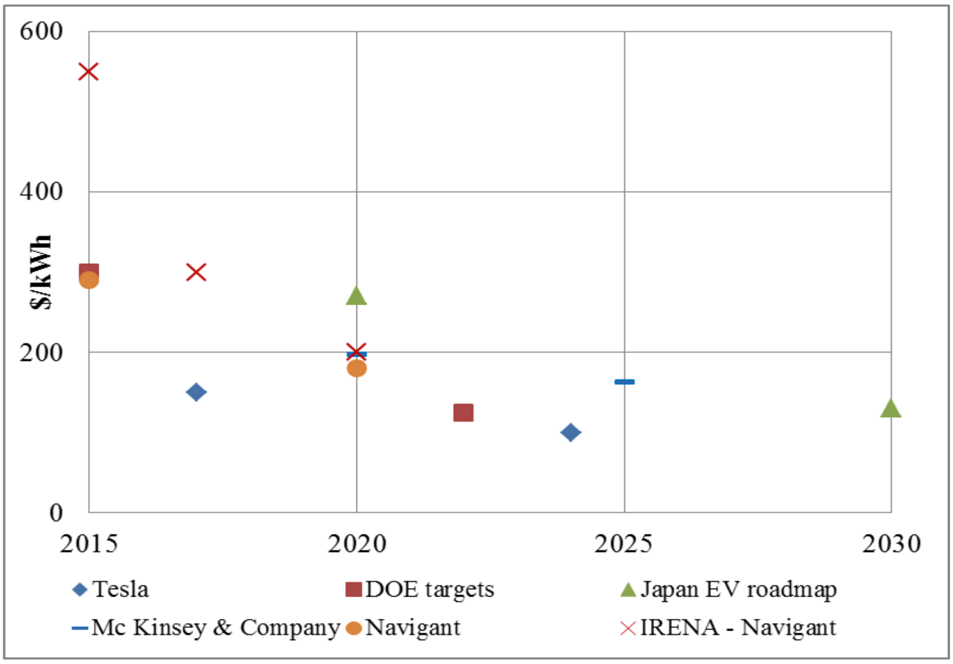


Figure 18: Li-ion battery price projections

In conclusion, the estimated battery price would drop below 200$/kWh between 2020 and 2025. In addition, the price would be further fallen **between 100$/kWh and 150$/kWh in 2030 with a stabilized price.** These reduced prices of battery would bring synergies related to the residential or commercial usage of the PV systems.

2 Analysis of PV usages with SWOT analysis

2.1 Introduction

In this part, the territorial application of PV system is studied with SWOT analysis. **Figure 19** summarizes the evolution of PV usage over time. Along with the development of PV technology and PV cost reduction, the PV usages have been diversified and the level of centralization has increased.

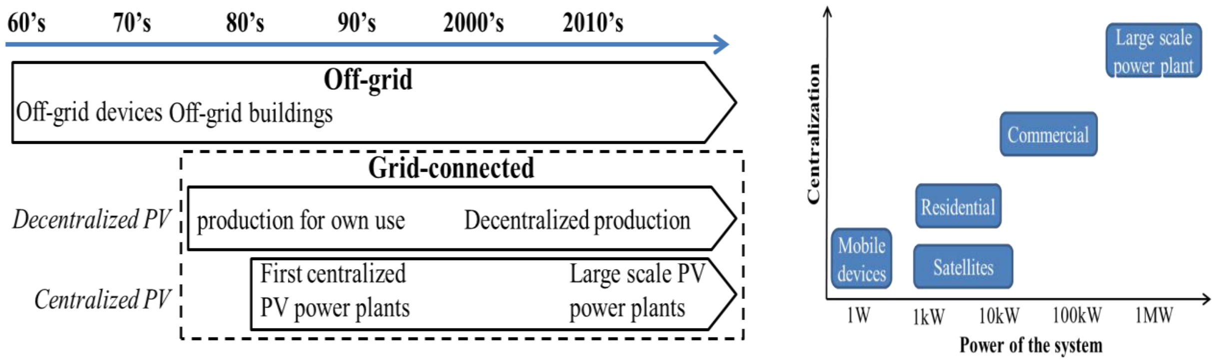


Figure 19: Change over time in PV usage

2.2 SWOT analysis

The characteristic of each segment is analyzed using the method of SWOT analysis. A SWOT analysis is a commonly used method in business to define strong and weak points of internal resources of a firm and external environmental factors like opportunities and threats that can be faced in the marketplace. The aim is to define the most effective strategies for business decision makers. This methodology can be also used for policymakers. Strong and weak points of each usage of PV power are defined. In addition, potential opportunities and threats are considered when applicable since it is helpful to prepare future strategies for further PV growth. Therefore, in terms of each market segment, strengths, weaknesses, opportunities and threats are organized using the 2x2 matrix. The analysis ultimate aims to help policymakers prepare strategies to attain desired goals by using internal resources and external conditions in the best way. **Figure 21** indicates four possible strategies.

	Positive factors	Negative Factors
Internal	Strengths	Weaknesses
External	Opportunities	Threats

Figure 20: SWOT 2x2 matrix

	Strengths	Weaknesses
Opportunities	O-S strategies	O-W strategies
Threats	T-S strategies	T-W strategies

Figure 21: SWOT strategies

- OS strategies: use strengths to take advantage of opportunities
- OW strategies: overcome weakness by taking advantage of opportunities
- TS strategies: use strengths to avoid threats
- TW strategies: minimize weakness and avoid threats

2.3 Historical off-grid systems and nomad usages

The first solar cell was created in 1954 at Bell Laboratory. The first targeted use of PV power was the ***nomad usage*** to provide electricity to isolated or autonomous equipment. PV technology was suitable for providing power to isolated devices, in particularly, with technical constraints that include low energy consumption, long life cycle, and low maintenance (e.g. traffic signal system, rescue terminals or scientific instruments). The usage for space satellite well fits to overcome the technical constraints associated with the weight of the satellite (this excludes many other technologies). A small PV cell (less than 1W) was used for the Vanguard I space satellite to power the radio (U.S. Department of Energy).

In 1963, Japan installed a 242W PV solar panel coupled with a battery to power a lighthouse on Ogami Island; it is the first off-grid application for a building (U.S. Department of Energy). In the 1970s, the cost of the solar cells dramatically dropped and it began to be used more widely for isolated devices (navigation warning lights, lighthouses, oil platform signal, foghorn, calculator, etc.) (NREL, 2011).

In the early 1990s, the PV system was still driven by off-grid applications (e.g. remote electrification). Off-grid systems gave a proper solution to power isolated areas where the cost of the grid extension was too expensive. To provide stable enough electricity, the off-grid PV systems are coupled with a battery system to store the electricity and provide it when the need exists.

However, the grid-connected PV market became more popular and the off-grid application now has a very small part in the global installations; less than 1% of the cumulative installed capacity of IEA PVPS countries in 2013 (IEA PVPS, 2014). Nowadays, the off-grid PV power is mainly used in the professional (INES, 2007) remote areas or for the electrification in rural areas or in developing countries (Hoffman, 2006).

Table VIII describes key characteristics of internal and external factors of off-grid application.

Strengths	Weak points
Power supply in remote areas (industrial & residential) Good application solution for the electrification in developing countries or rural areas	Intermittency Costs for storage devices
Opportunities	**Threats**
Energy poverty in the world: 18% of global population lack access to electricity (IEA website) Hybrid system coupling with diesel or other renewable sources (e.g. wind, hydro)	Oil price drop

Table VIII: SWOT analysis of off-grid application

Therefore, **the off-grid PV system has great potential to supply power for the following cases.**

- Rural or remote areas that are not connected to the grid: the development of electric line systems often require high construction costs, and PV systems can replace diesel generators for power supply
- Areas which are connected to the grid, but with low reliability of power supply and frequent power failure due to grid problem

In conclusion, off-grid systems give a solution to solve the global energy poverty problem (OS strategy). Significant parts of world's population mostly in sub-Saharan Africa or rural areas in developing Asia still have difficulties to access to electricity, electric light, water pumping for irrigation, or clean cooking facilities (IEA). The electricity supply problem can be also found in other regions like South America, Central Asia and Central America. Many of these areas have a better weather condition to produce solar PV power than many locations in developed countries where solar PV demonstrated a rapid growth over the last decades.

2.4 Grid-connected systems

2.4.1 Introduction

Off-grid systems have limitation when the PV electricity production does not match up with the electricity consumption. The generated electricity, which is not consumed or stored, will be lost. The electricity consumption cannot exceed the power capacity of PV system. The grid connection addresses these issues. Furthermore, on-grid PV systems also supply electricity to the buildings connected to the electricity network.

However, grid-connected system has its limits in terms of *grid stability* (e.g. overloading, congestion issues by excess power export, or power quality degradation). These problems are location-specific; some local areas, which have weak grid infrastructures or excess grid congestion, will encounter more problems than other regions that have solid grid systems with little grid congestion. Technological progress sometimes provides better performance levels to maintain the grid quality; e.g. advanced inverters support better network stability. The PV self-consumed model can be a good solution in congested areas within the grid.

On-grid systems can be largely classified into ***distributed systems*** and ***centralized systems*** according to the system size and purpose. The size of distributed PV systems is usually less than 100 kWp. However, the centralized PV systems exceed 1 MWp. The PV systems generally have three different installation types; ground-mounted, roof-mounted or integrated in the building (BIPV)[31].

The below Table IX demonstrates possible market segments of grid-connected PV systems.

Type of grid- connection / Type of installation	**Grid-connected PV systems**			
	Distributed			***Centralized***
	residential	*commercial*	*industrial*	*utility-scale*
	<10kWp	>10-100kWp	>100kWp-1 MWp	>1MWp
Ground -mounted			O	O
Rooftop-mounted	O	O	O	
Integrated to façade or roof (BIPV)	O	O		

Table IX: Market segments of grid-connected PV systems

2.4.2 *Distributed PV systems*

Distributed PV systems aim to provide electricity to grid-connected customers or to the network. In 1973, the University of Delaware built a residence 'Solar One' using a roof-integrated PV system; this was the first PV system connected to the grid with a meter and the grid was used as a backup solution (U.S. Department of Energy). Distributed PV systems have developed with the implementation of remuneration scheme for PV electricity supply in the early 2000's.

Grid-connected distributed PV systems can be segmented into three parts according to the size of system. First, the typical size for residential systems is normally from 1 kW to 10 kW. Secondly, PV systems above 10 kW and not exceeding 100 kW are included in the commercial systems. Both residential and commercial systems have two possible installation methods; rooftop-mounted system or building-integration. In addition, the PV system which exceeds 100kW and less than 1 MW are usually used for the industrial purpose.

Table X identifies strong and weak points of grid connected distributed PV systems.

Strengths	Weaknesses
Stable power supply thanks to the grid Reduced distribution losses when PV system is installed at the point of use No need for extra land use Substitute of building materials (e.g. BIPV)	Costs (incl. systemic costs) Risks related to grid interconnection (e.g. overvoltage, unintended islanding for low/ middle voltage network)
Opportunities	**Threats**
Low carbon policies Low consumption or positive energy buildings for energy transition Desire for energy independence Smoothing via geographical spread on a large area	Stability of the grid at high penetration level Inadequacy with the consumption profile

Table X: SWOT analysis of grid-connected distributed PV systems [32]

The building sector, residential or non-residential, consumes an important share of the energy; for example, it accounted for 40% of total final energy consumption & around 55% of electricity consumption in the EU-28 in 2012 (Intelligent Energy Europe Programme of European Union, 2015). Therefore, the reduction of its share in energy consumption is a main target of the energy public

[31] The ground-mounted systems concern that the support of the module is on the ground. The rooftop systems are mounted on top of an existing roof or PV systems can be fully integrated to the roof replacing the tiles (IEA, 2010).
[32] IPCC 2011, (IEA PVPS, 2008b; ECOFYS, 2007)

policies (e.g. energy saving, positive energy buildings). Moreover, some electricity users have a desire of energy independence (for example, the collaboration between Solar Edge and Tesla capitalizes on this desire (Solaredge, 2015). The decentralized PV systems provide a solution to these issues with an **OS strategy.**

However, the installation of PV system on a roof is more complex than a ground-mounted system inducing extra costs. The **reduction of the costs** is still possible mainly in terms of **soft-costs** and an **OW strategy** is possible to address this issue, supported by energy saving public policies.

The impact of the penetration of the PV electricity in the grid is an important issue. The decentralized PV is usually installed on already grid-connected buildings and small-decentralized PV systems spread on a large area can smooth the intermittency. Therefore, a **TS strategy**, like **self-consumption**, seems possible to reduce the **impact on the grid**.

The last threat is the inadequacy between the PV production and the local consumption. Two **TW strategies** can be studied to overcome this threat by developing **storage system**, or, more easier, by choosing buildings where **the consumption profile best matches the PV production**, like commercial, small industry or office buildings.

2.4.3 Centralized PV systems

Centralized PV systems supply electricity as centralized power stations. These systems are ground-mounted and not associated with a particular electricity customer. The solution is based on the scale effect to reduce the installation costs. Since they aim to give bulk power, the typical size of centralized PV systems exceeds 1MW. Since the middle of the 2010's, promoted by attractive remuneration schemes of PV electricity, many megawatt scale PV projects have been developed (see **Figure 22**). For example, on June 19 2015, the Solar Star power plant was installed (579 MW[33]) in Antelope Valley in California and the generated power was fully sent back to the network.

Figure 22: Megawatt scale PV power plant (INES, 2007, p. 10)

Strong and weak points of grid connected distributed PV systems are presented in the following Table XI.

Strengths	Weaknesses
Cost reduction via scale effects in terms of installations, operation costs, and the BOS costs	Costs compared with other technologies in the electricity market, Intermittency and not dispatchable, Land usage
Opportunities	**Threats**
Energy transition	Fuel prices, grid management

Table XI: SWOT analysis of centralized grid-connected PV system

[33] 1.7 million of crystalline silicon cells were used on the surface of about 13 km^2, (Wesoff, 2015).

There are many advantages to promote centralized grid-connected PV systems **with an OS strategy** utilizing the opportunity of energy transition and public policies.

However, large PV power plants are rarely competitive compared with other classic power plants in the electricity market. Therefore, the weakness and the threats should be fixed in priority. Different **TW strategies** are possible to promote centralized grid-connected PV systems. It can target the areas where the PV production has the lowest LCOE or the electricity consumption best matches with the PV production (e.g. **sunbelt regions**). In addition, in order to reduce **land usage**, a good strategy is to avoid the usage of fertile lands; it should **focus on 'bad lands'** like deserts. Another way is to promote the use of **high efficient PV system**s like CPV; the use of high efficient PV systems reduces the land usage to produce the same level of PV output. Moreover, the PV electricity is not dispatchable; a **storage system** can give a solution for the large-scale penetration of PV systems.

2.4.4 Grid connection options

PV systems can be connected to the grid according to different options. Some countries allow PV systems to feed 100% of the electricity produced into the grid (in front of the meter grid connection), while others only allow the transfer of excessive PV output after onsite-consumption (behind the meter grid connection) in the grid. The first mechanism is related to *the FIT scheme* policies, whereas the latter is mostly associated with policies like *net metering* (IEA-RETD, 2014; EPIA, 2013).

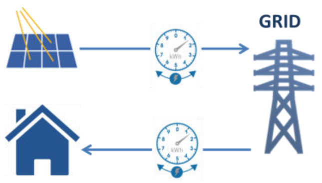


Figure 23: FIT scheme

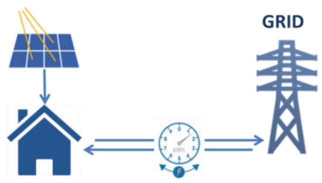


Figure 24: Net metering scheme

- ***FIT scheme:*** PV installers are allowed to transfer all electricity produced to the grid and consume electricity from the grid. The injected electricity will be compensated on the basis of pre-defined tariffs during a fixed period, and they will pay for the electricity consumed according to the applicable electricity rates (IEA PVPS, 2014).
- ***Net metering system:*** End-users who produce electricity from PV systems are allowed to inject excessive electricity into the grid (the difference of PV output to onsite consumption). Billing will be calculated on the basis of the net electricity from/to the grid during the applicable period (IEA, 2014b; EPIA, 2014).
- ***PV system +storage:*** PV systems can be self-consumed without connecting to the grid. In this case, a storage system is needed. This can be considered as an option to provide power to isolated areas, which mostly relies on fossil fuel generation (IEA-RETD, Op. cit.).

FIT and net-metering policies differ from one country or state to the next, e.g., different rates are applicable in terms of the compensation amount or level, and often different strategies are in place with respect to the instantaneous consumption of onsite production. The self-consumption system combined with the net metering system has developed in several countries like the US, Japan, Canada and some European countries, based on different legal frameworks (REN21, 2014).

2.5 PV future usages

PV systems are still expensive and compete with other solutions. The main objective of PV policies is to make PV power more competitive in the electricity mix. The coupling of PV system with other sectors can be a smart solution to reduce the cost of PV systems because different sectors can share common components or processes. The possible coupling for PV systems concerns two areas;

- **PV system materials**: PV system can share components with other systems
- **New market creation** for PV electricity

The coupling with PV system with the construction sector is a good example for the first case; PV system materials can replace the tiles on the roof and this reduces PV system costs (INES Op. cit.). The concept of solar road that can replace an asphalt road also gives a good example. The coupling of PV power with the use of electric vehicle's batteries is another new usage to optimize the consumption of the PV electricity and to share the cost of the battery. Moreover, this coupling can be useful for the network balancing (Kempton, et al., 2015).

In terms of new market creation, there are some emerging possibilities to optimize the use of PV electricity. For example, the creation of gas (H_2, biogas) gives a good solution to store the electricity when it is not profitable; the created gas can be used as a transport fuel or traded in the gas market (Ajanovic & Haas, 2015). It can also generate electricity when the electricity becomes profitable. The advantage of this solution is to enlarge the PV power's potential market towards the whole energy market. In addition, it allows policymakers to have broader base to reduce CO_2 emissions.

In this regard, in the distant future, the development of the storage solution coupled with the intermittent renewable electricity production will solve the intermittency problem of renewable energies. The PV system with its storage system based on appropriate economic feasibility will give a solution to grid balancing and network reliability.

3 PV integration in energy system

In this section, the study examines the impact of the integration of photovoltaic energy in the electricity system. From our analysis of PV usages using SWOT analysis method, we have found that the intermittency of PV power is a big threat. Therefore, the integration of intermittent production of PV electricity into the energy system presents diverse constraints and challenges in terms of the system and market operation. They will become more obvious with the large-scale penetration of PV power into future electrical supply systems. To understand the issues well, this study first gives a brief understanding on the ground principles of electrical power systems to explain how they are planed and operated and to define their major constraints. Based on this explanation, impacts of the PV integration in electrical power systems are studied. The study raises questions about the systemic costs of PV electricity; the last part of this section identifies the important impacts that need to be considered by policymakers.

3.1 Overview of the electricity market

An electric power system is electrical equipment's network that is used to supply, dispatch and use electric power. It is generally divided into four processes (Saguan, 2007): electricity generation, transmission, local distribution and consumption (**Figure 25**).

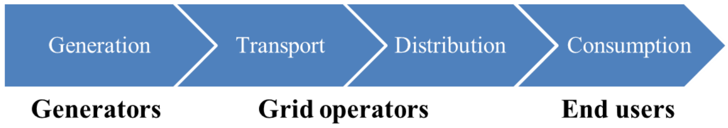


Figure 25: Four processes of the electric power system

The power generation and the electricity transport must respect some physical laws:

- In terms of power production, the time to respond to power request and the scope of power variation are different depending on the type of power plant.
- A limited amount of power can go across the line.[34]
- Alternative electricity (AC) is used on the network and the different power plants must be synchronized in terms of frequency and phase.

The monopoly through vertical integration from the production, power supply to end-users was the most common model before the electricity market liberalization in the 90's in the majority of the industrialized countries (Tehrani, et al., 2013). Different kinds of competitions exist in the electricity market; e.g. competitions between generators with different purchasing agencies or in the wholesale market, and retail competition.

However, the grid management is seen as a natural monopoly; a single company manages the whole network of electric power transmission or power distribution. These processes are regulated for a fair usage of the grid (Esnault, 2013).

Some regions have organized electricity market where electricity is traded according to consumer needs. In Europe, the electricity market model promotes competition among power producers in a wholesale market and sellers in a retail market. The wholesale market is composed of an over-the-counter (OTC) market, where bilateral agreements are concluded, and power exchange market (pools) (Stoft, 2002). The market is operated before the electricity is needed. However, in order to maintain the security of electric power system, a market for the short-term (some minutes) balancing exists, which aims to adjust the production to the demand when deviations are observed between the forecast and actual demand (balancing or ancillary services market). The market design in Europe is presented on **Figure 26**. The electricity market design generally aims to support long-term investment of generation capacity and network to secure energy supply to meet demand at least cost.

[34] The transport of electricity is subject to the Kirchhoff's current laws that define the performance of electrical circuits .

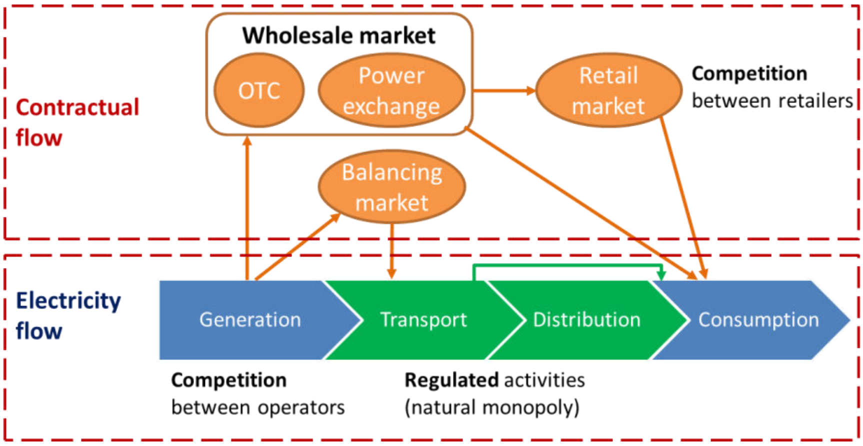


Figure 26: Electricity market design in Europe (Ministère de l'écologie, du développement durable et de l'énergie of France, 2015)

3.1.1 The electricity production mix

The power plants produce on demand of instant electricity consumption. In order to meet electricity demand and its variations, an electricity mix is largely composed of 1) ***base-load power plants*** that produce the maximum output almost all the time, and 2) ***peaking power plants*** that can follow the fastest variations of demand. Between these two categories, the term of ***mid-merit power plants*** is sometime used to describe power plants that have enough flexibility to follow the slowest variations of demand of the day.

The choice of power generation plants that compose the electricity production mix depends on economical and technical specifications. The economical specifications of a power plant are decided depending on two main criteria, which are 1) the **investment cost**, and 2) the **variable cost** including fuel costs and the operation and maintenance (O&M) costs. The costs of the electricity output depend on the on the amount of electricity produced in a year. The electricity production depends on the load factor, which is the ratio of its actual output over a period of time to its potential maximal output over the same period of time, and the lifespan of the plant. The electricity pricing can give an economic assessment using the method of **Levelized Cost of Electricity** (LCOE).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

With

n the lifespan of the system in years

I_t the investment cost during the period t

M_t the operating and maintenance costs during the period t

F_t the fuel costs during the period t

E_t the electricity production during the period t

r the discount rate

Equation 1 : LCOE formula[35]

[35] The weighted average cost of capital (WACC) is referred to as the discount rate. *r (cost of capital).*

Base-load power plants with low variability are generally characterized by high investment costs but low variable operating costs, while peaking power plants with high variability are generally characterized by low investment costs but high variable operating costs. Table XII gives the costs of traditional power plants.

Technology	Investment cost (€/kW)	Variable costs (€/MWh)	
Nuclear	2688 - 4909	37.4 – 60.4	Base
Coal	497 - 2786	38.5 – 92.3	
Natural gas	423 - 1288	34.6 – 92.3	Peak
Hydropower	718 – 3125	2.5 – 24.6	

Table XII: Fixed and variable costs of traditional dispatchable power plants (Cruciani, 2014)

The technical specifications depend on the technology employed and the fuel used. For example, fossil fuel power plants cannot be started immediately because the temperature of the boiler must rise progressively to avoid thermal shock. In terms of nuclear power plants, the power variations produce elements that reduce the efficiency of nuclear reaction. All these limitations should be considered for the effective planning of production capacity usage.

Technology	Startup time (min)	Maximum power variation (%/min)	
Nuclear	2 h to 2 days	1-5%/min	Base
Coal	1-10 h	1-5 %/min	
Natural gas CCGT	30-60 min	5-10 %/min	
Natural gas OCGT	10-20 min	20 %/min	Peak
Pumped Storage Hydroelectricity (PSH)	Very short	40%/min	

Table XIII: Startup time and maximum power variation of traditional power plants (Cruciani, 2014)

3.1.2 *Electricity price formation mechanisms*

The optimal management of electric power system is to rank the capacities according to the ascending order of short-term marginal costs of production (**merit order**). The ranking is organized based on the day-ahead declaration of available capacities. The base-load capacities have low variable costs and they are ranked first (e.g. run-of-the-river hydroelectricity, nuclear). The peaking capacities have high variable costs and they are ranked last (e.g. oil, gas).

Under the uniform pricing model, the electricity price is adjusted according to the marginal cost of the last power plant utilized and all other producers receive this price for their electricity[36]. With this system, base-load power plants receive the surplus revenues, called *infra-marginal rents*. The base-load capacities have high investment costs compared to the peaking units and the merit order allows producers to recover their investment costs. In an **energy only market**, the generators who do not produce receive nothing.

[36] Another way is the 'pay as bid' where producers receive the price they asked for.

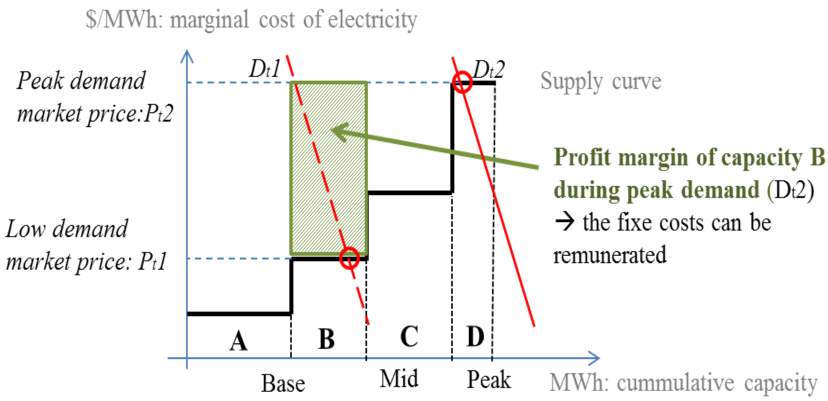


Figure 27: Merit order and electricity price formation (Haas, et al., 2013; Commissariat Général à la Stratégie et la Prospective (CGSP), 2014)

However, an issue exists regarding the extreme peaking capacities that cannot cover their fixed cost (Hogan, 2005) (the **missing money).** This phenomenon discourages investors to install this type of capacity, even though it is crucial for the balancing of the system. A scarcity rent may exist if the extreme peak marginal capacities are allowed to ask a higher price than their variable costs (Finon, 2013). Other solutions exist like a **capacity market** that finances the extreme peak capacities or a **load management** that remunerates some consumers that accepts to reduce their electricity consumption during peak (Percebois, Nov. 19th 2012).

3.1.3 Optimal electricity production mix

Since each type of power plant has different investment costs and variable cost, their operation time in a year varies to design optimal electricity production mix. The optimal operation mix is obtained based on the production cost; **Figure 28** gives an example. There are four types of capacity: two gas power plants with low fixed costs and high & medium variable costs, a coal power plant with medium investment costs and medium variable costs, and a nuclear power plant with high investment costs and low variable costs.

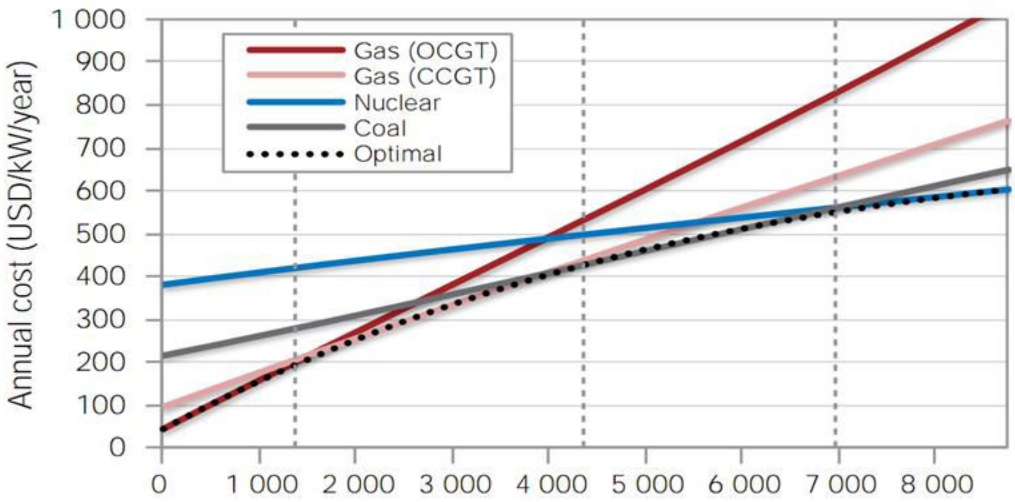


Figure 28: Example of mix optimization with gas, coal and nuclear capacities (OECD/NEA, 2012, pp. 133, Ch. 4, Box 4.4)

The abscissa gives the number of hours in a year (8760 hours). The cheapest technology is used during a given operating time of a year to obtain an optimal mix. For example, the OCGT is installed when the usage requires less than 1300 hours of operating time, the CCGT between 1300 hours and 4300 hours, the coal power plant between 4300 hours and 7000 hours, and the nuclear power plant more than 7000 hours.

To identify installation capacity of each power plant, the optimal mix must be correlated with the consumption profile. **Figure 29** gives an example with France case; the required power capacity for each unit of time (quarter of hour-to-hour, see the graph on the left) is ranked in decreasing order (see the graph on the right). The obtained curve is called the **load duration curve**.

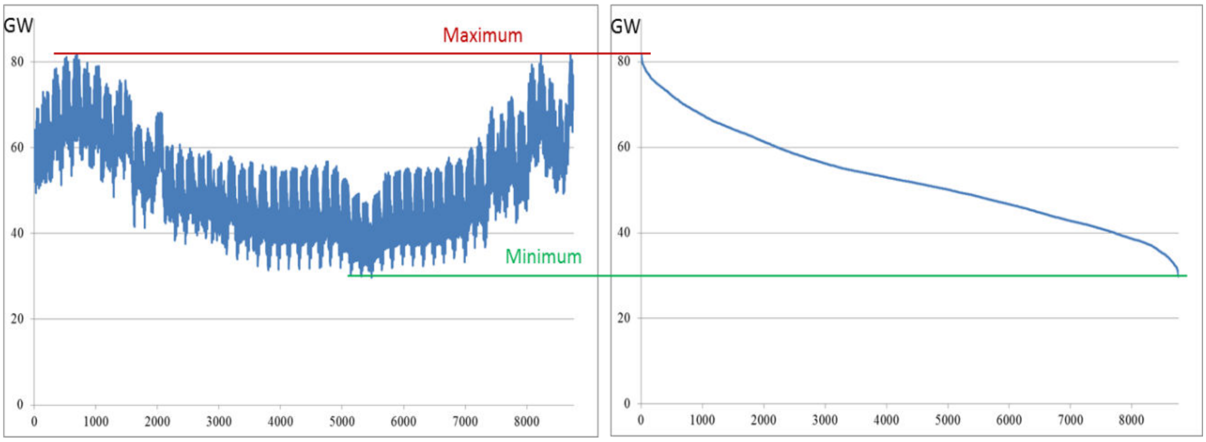


Figure 29: Hourly consumption profile in France in 2014 and load duration curve[37]

Then, the optimal usage of the mix is projected on the load duration curve and the optimal installed capacity of each power plant is deduced (**Figure 30**). Based on this example with the French load duration curve with four different types of power plants[38], it can be drawn that the optimal mix gives about 40 GW of nuclear capacity to install, 10 GW of coal power plants, and 15 GW for CCGT and OCGT each.

[37] Created by author with RTE – eco2mix data (RTE).
[38] This is a simplified model, in reality, more types of power plants can be used.

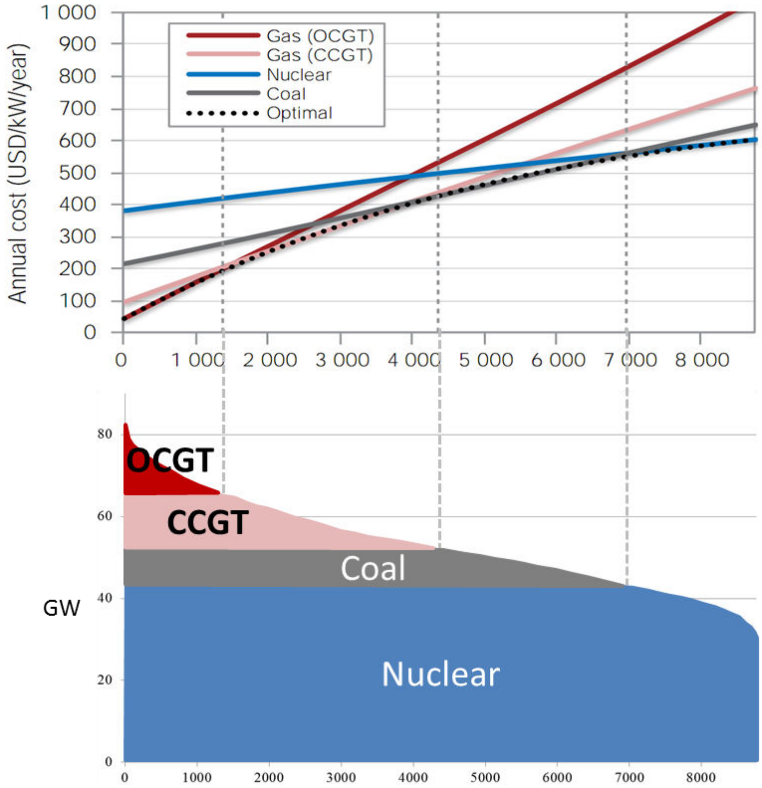


Figure 30: Example of optimal mix based on load duration curve (OECD/NEA, 2012)

3.2 Electricity supply-demand management

The specificity of the electricity market is normally associated with uneconomical characteristic of large-scale electricity storage[39]. Therefore, the power plants must generate the requested electricity to meet electricity demand at any moment.

Electricity demand is characterized by 1) significant variations, 2) the difficult forecasting with precision, and 3) the very low price elasticity. Electricity demand varies according to climatic considerations, economic profiles, and consumption habits. In addition, it has a different aspect depending on period of time; night/day alternation, weekly change (weekdays vs. weekend/holidays) or seasonal changes (summer vs. winter). A change in the demand can be rapid and significant.

Each country has different features of electricity demand. To give an example of this variation, **Figure 31** displays the French and German electricity consumption profile[40]. In France, the winter electricity consumption is about two times that of summer, mainly because of the use of electric heaters. The peak demand for electricity consumption in France is in the evening of winter; for example, during winter 2011-2012, an historical record was set at 101.7 GW (at 7 pm on February 8th 2012) (Le Monde.fr, 2012; Haessig, 2012).

[39] Except when the geography allows water-pumping storage

[40] Even though these two countries neighbor with the similar level of economic development, their consumption profiles are different.

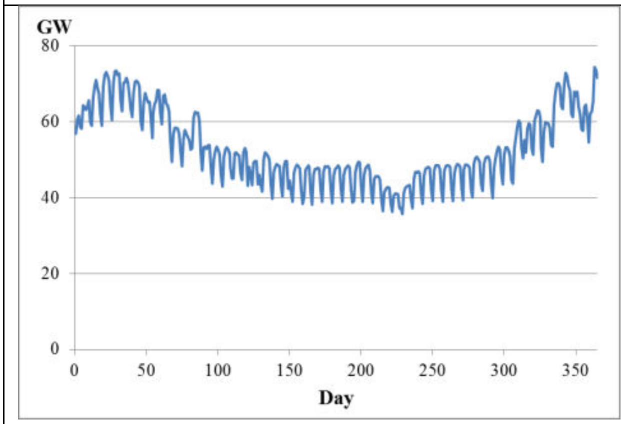
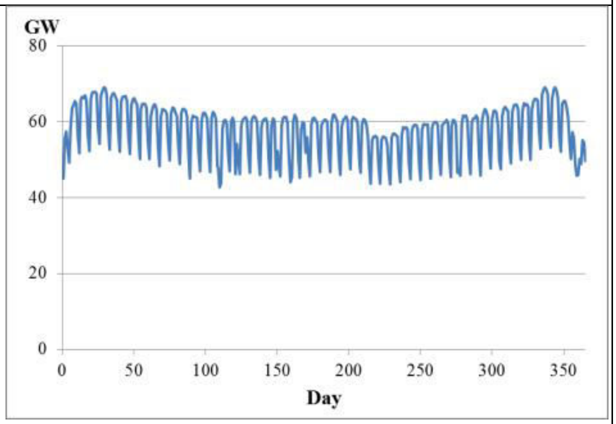
Daily average electricity power consumed in 2014 (France)	Daily average electricity power consumed in 2014 (Germany)
	

Figure 31: Consumption profiles in France and Germany[41]

Power generation should be planned to match the demand variations at any time, all year around (Saguan, 2007, pp. 23-24). A stable infrastructure of network to supply that power is compulsory for the successful balancing of power supply and demand. The mission of the electricity network manager is to ensure the balancing between power production centers and the consumer demand at any time.

The frequency is a good indicator for the equilibrium management of electrical system. It is thus important to maintain the frequency as stable as possible to its reference value (e.g., 50 Hertz (Hz) in Europe and 60 Hz in Northern America) for the security of the system. A difference in the nominal value can cause damages on electric devices.

As seen, the power plant operation program depends on economic (e.g. operating costs) and technical features (e.g. turn on/off time). The method of balancing of power supply and demand differs according to the time-period basis.

In terms of long-time period (e.g. 30 minutes to 6 to 24 hours), unit commitment method is used to plan an optimal electricity mix to meet electricity demand throughout the day; 1-2 day ahead planning is deployed to prepare an hourly or half-hourly program of power generation to address forecast demand at least cost. The merit order is applied; **base-load units** generate power at their maximum capacity all day, **peaking units** run during the times of peak demand, **mid-merit units** operate to correct the flaw between two units (e.g. turning on in the morning and off at night). However, the shorter-term balancing (e.g. minute-to minute basis) is automatically done by generation control center. The load following is used to meet moment-to-moment electricity demand. Dispatchable power units are able to control their output between a minimum and maximum level, however, intermittent power units (e.g. wind, solar) have difficulties to control of generation (IPCC 2011). Furthermore, in order to ensure the stable supply of power to meet the demand, the balancing planning should be extended to longer time horizon (e.g. next few decades) because the construction of power plants and network require a long time with large investment of capital.

[41] Created by author based on RTE data (RTE)

In this context, to ensure the equilibrium of power supply and demand, the network manager plans ahead the production capacity based on demand forecast & historical data of power consumption and weather forecast (see **Figure 32**). If the difference in the frequency appears during the day, the network manager instructs to reduce or increase production capacities. Each operation to re-adjust the equilibrium is expensive. Therefore, the better the demand is forecasted, the cheaper the grid costs will be.

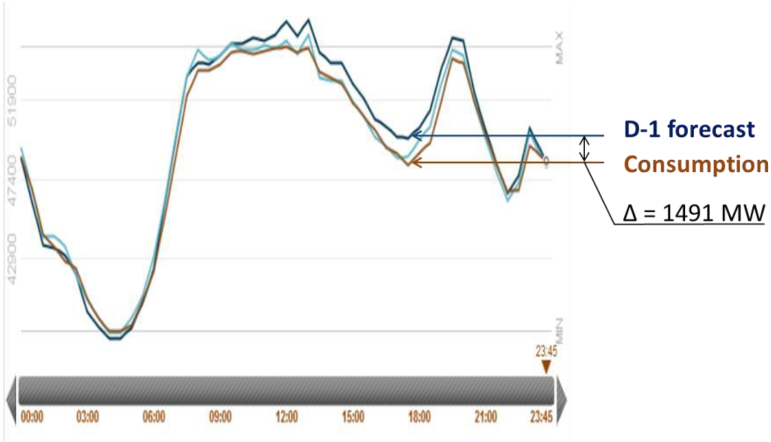


Figure 32: Day-ahead forecast and consumption for October 17 2014 in France (RTE).

In addition, the electrical system must consider power losses in transmission. If the distance between power generation centers and consumption sites is short, there will be less transmission loss. Furthermore, the balancing should also consider the cases of plant failure, local network faultiness, or maintenance to ensure the stable electricity supply at any time. The system maintenance or upgrading schedules should be calculated in advance to prevent unexpected breakdown or power failure that can affect the national energy supply security. Otherwise, a risk of network failure can be caused; e.g. a blackout in August 2003 in USA [42] and in November 2006 in Europe (European Regulators' Group for Electricity and Gas (ERGEG), 2007).

In this regard, the electrical system is very constrained and it must be organized according to the consumption profile, the available electricity mix, and the quality of the network. In summary, the balancing of power supply and demand must guarantee the following;

1) The **Short-term balancing**
2) The **Long-term back up**

Furthermore, **the longer-term investment decisions in generation capacities and transmission infrastructures** should not be ignored for the secure balancing of electrical power system.

[42] Due to little unbalancing of few 100MW followed by a 100MW variation. (New York Independent System Operator, 2004)

3.3 Integration of PV power in electricity system

3.3.1 Introduction

Electricity generation using renewable energies gives a new approach of contribution in the electricity mix compared with traditional energies. In order to increase the share of renewable energies in the present and future energy mix, integration efforts are needed. They normally require investment to promote new organizations (innovation costs[43]). The accurate understanding of PV energy and its availability will be a basic step in terms of integration efforts. Furthermore, other changes in various sectors are also needed: e.g. institutional frameworks, innovative approach, improved social aspects, market planning, etc.

The specificity of the PV energy is related to its intermittency (Hirth, et al., 2015). The following points represent PV production characteristics.

- PV production is variable depending on daily time period, seasonal variations and the weather conditions
- PV production depends on the geographic location
- PV production has some unreliability directly linked to uncertainty of weather forecast

The variability of PV energy requires high integration efforts with objective of keeping the stable energy supply system. In this regard, an illumination on systemic effects of PV electricity is useful to find strategies for systemic innovation to integrate PV energy in electricity mix with least innovation costs.

3.3.2 Systemic costs of PV energy

As shown with the SWOT analysis in chapter 2.2, the use of PV connected to the network includes many threats related to PV integration in the electricity system; they are mainly associated with network management issues because of the intermittency.

Power generation plants coexist with other parts of energy mix. They influence each other and interact with customers through power grid, affected by a set of conditions (technological, natural resources, socio-economic environments, etc.). Therefore, the cost of each plant should be calculated under this context. For example, intermittency, network congestion or impacts on energy security should be included while calculation the real costs of individual power plant (this will change the economic calculation for investors). However, existing studies on PV economics are mainly based on LCOE and grid parity. It is important to keep in mind that all power plants cause system effects (OECD/NEA, 2012).

In this regard, a review on system effects has its importance to give a comprehensive & accurate perspective of solar PV costs in the energy mix. The total system costs have three levels; plant-level costs, grid-level costs and other systemic effects (OECD/NEA, Op. cit.).

[43] Quoted from N. Popiolek

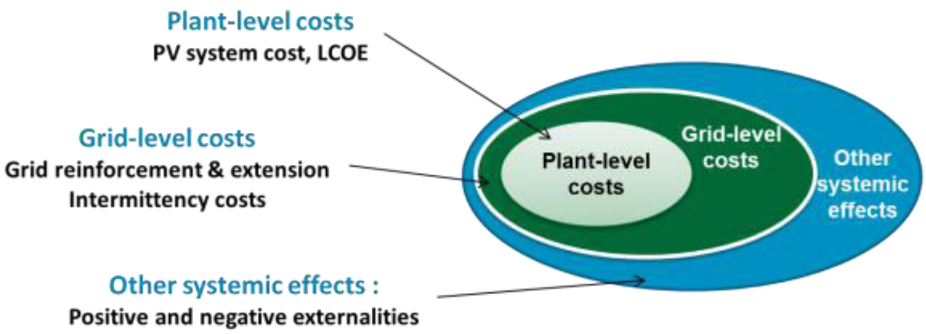


Figure 33: Total system cost of PV (OECD/NEA, 2012)

Most considers plant-level costs as costs of PV electricity. The plant-level cost is directly related to the levelized cost of PV electricity (PV LCOE). This cost is used as a reference cost in the international studies (Fraunhofer, IEA PVPS, IRENA, EPIA, etc) to follow the progress of the PV technologies. However, this indicator is limited to fix the real cost of the PV installation in the energy mix (Hirth, et al., 2015; Joskow, 2011; Ueckerdt, et al., 2013). The electricity system is very constrained and the increase of the penetration of non-dispatchable energies, like wind and solar PV, influences the balance of the whole electricity system.

Taken the characteristics of intermittent PV power into account, the grid-level costs with large penetration of PV power became significantly important. Therefore, the grid-level costs are studied in the following section.

3.3.3 Grid-level costs

As said, PV power plant interacts with other power generation plants, and customers through the power grid. PV power plant has two way of using power grid. First, the generated PV power can be directly used onsite where it produced (off-grid systems or self-consumption); this reduces the use of grid. Secondly, PV production can feed the generated power back to the traditional power grid; PV power follows the traditional way of using power grid from power plants to customers.

Without an appropriate solution of storage of PV electricity, the PV system needs to be connected to the grid. Intermittent PV electricity is not able to meet the electricity demand at all seasons of the year. The concept of 'grid-parity', which compares PV LCOE with the electricity retail price, is not enough to identify the competitiveness of PV electricity in the electricity mix. In addition, electricity retail price often include grid management costs; e.g. about 1/3 of the retail electricity price in France is used to finance the grid and its management. In this regard, the grid-related costs should be integrated to give the real cost of PV electricity.

Even though intermittent PV energy has a low load factor compared to conventional energy sources, the network should support the maximum capacity of PV electricity that can be generated during PV production peaks or meet demand that can be requested when PV power plants are not available. Compared to other centralized and dispatchable technologies such as nuclear, the grid-level costs for PV energy may be much higher (OECD/NEA, 2012).

The grid-level costs rise with the increase of variable energies in the electricity mix. In addition, the grid-level costs are **country-specific**, strongly depending on **penetration level**.

OECD largely divided the grid cost into two parts: 1) additional investments to extend and upgrade the existing grid, and 2) the costs for increased short-term balancing and for maintaining the long-term adequacy of electricity supply to integrate variable energies (OECD/NEA, Op. cit.) (Hirth, 2014).

1) Grid extension and upgrading

PV system integration requires additional costs to strengthen the grid of transportation and distribution. The **grid upgrading costs** include the costs related to grid reinforcement and extension.

- Grid reinforcement: the current grid upgrading to adjust voltage or load-carrying capability
- Grid extension: the existing grid extension to connect plants to the current grid

Those costs are mainly related to the local production compared with the local demand. Additional costs in term of grid upgrading are inevitable when PV system is installed in areas with a structural production surplus. In addition, the network quality and power trade amounts also influence the grid-level costs.

For residential or commercial PV systems, the grid connection costs are already integrated in soft-costs of PV system costs since the buildings are already grid-connected. For utility-scale PV plant, the grid extension is needed and its costs are high because PV power has low load factor. In this case, the power line must be sized on the maximum PV output even though PV systems produce at its maximum level only during a short time of a year.

2) Grid balancing

Photovoltaic energy produces during daytime and is not dispatchable. The integration of PV in the existing grid requires additional costs to deal with the intermittency of PV power. Therefore, additional costs should be considered in terms of **balancing the grid** and preparing **back-up capacities** especially during the evening consumption peaks.

- **Short-term balancing:** second-by-second matching of electricity supply and demand (e.g. real-time adjustment, the day-before forecast) → *Demand(t) = Supply(t)*
- **Long-term back up:** provision of dispatchable back-up capacity to satisfy electricity demand at any moment (peak) → *Installed capacity of plants = Peak demand load + Reserve margin capacity*

The short-term balancing concerns the second-by-second balancing of electricity supply and demand; it is closely related to the accuracy of weather forecast and the predictability of supply and demand because the improved forecast and prediction would decrease the uncertainty in supply and demand. In addition, more importantly, the level of flexible capacity in the electricity mix and the size of interconnected electricity system influence the balancing task in term of instantaneous adjustment to match changes in demand. Therefore, countries that have a large share of flexible technology capacities (e.g. hydropower) in their energy mix need less balancing costs.

Intermittent PV system requires the long-term dispatchable back up capacity to meet electricity demand at all times. Non-dispatchable energies like PV do not contribute much to generation system adequacy; every electricity system has reserve margin capacity on top of the peak demand load to ensure the system's reliability. The long-term backup costs include investment and operating costs to give additional adequacy capacity; this cost is necessary to maintain a certain level of system reliability when variable energies are integrated in electricity mix. The backup costs account for the large part of grid-level costs. In addition, there are other solutions that can compete with this; e.g. energy storage and demand-side management.

3.3.4 Other systemic costs (externalities)

The broader level of systemic cost should concern externalities of PV electricity in the electrical system. Externalities refer to positive or negative effects, which have not yet to be internalized into the PV system price. They influence the national energy system, economy and social welfare with respect to PV penetration into the energy system. There are various aspects to be considered: environmental, electricity market, technology, economic and energy position (OECD/NEA, Op. cit.).

However, it is extremely difficult to quantify externalities in a single unit; a qualitative approach can be employed to evaluate externalities of PV power in the energy mix. Table XIV indicates examples of important externalities of PV electricity.

<table>
<tr>
<td colspan="2">Environment
▪ CO_2 emission reduction (incl. back-up gas)
▪ Health
▪ Land usage
▪ Industrial accident
▪ Waste management</td>
<td>Electricity market
▪ Externalities on electricity system (incl.stakeholders' losses, grid)
▪ Reduced wholesales prices & decreased load factors of electricity mix
▪ Re-configuration of electricity system in the long-run</td>
</tr>
<tr>
<td>Technology
▪ Technological innovation</td>
<td>Economy (spill-over effects)
▪ Economic growth
▪ Industry competitiveness
▪ Trade balance and energy balance
▪ Employment : job creation, job shift</td>
<td>Energy
▪ Impacts on energy supply security
▪ Impacts on country's strategic position</td>
</tr>
</table>

Table XIV: Externalities of PV electricity

As said, the monetization of externalities is hardly possible dues to its broadness and complexity of the impacts. In addition, it is very challenging to distinguish externalities of PV power in the complex and dynamic system; a number of variables can simultaneously influence them.

Therefore, the attempts to calculate such externalities are often limited to environmental externalities, which can be considered with the reduction of the emissions of greenhouse gases or a fixed price for CO_2 emission. Furthermore, accident or waste issues should be considered as environmental externalities. Unlike conventional energies (e.g. coal, nuclear), PV energy does not require large spaces for waste disposal (IEA-RETD, 2014). Positive environmental externality is an important aspect when assessing PV integration in the electricity system. However, the increased use of gas to balance the system should not be forgotten.

The innovation of technology is another externality. With regard to PV development, many countries have been putting efforts in basic research to advance the PV technology for a large deployment. The technological capabilities give a positive impact to increase the national competitiveness and economic development (Álvarez & Marin, 2013).

In the development of PV sector, the economic benefit is one of the most important externalities that policymakers give priority, in particular, to recover the economic crisis. PV power creates jobs (Blyth, et al., 2014) in manufacturing, installation, service industries, and associated industries for the national economy (IEA, 2014c). A strategic choice targets the potential to increase national income through sales or exports, to improve the industrial competitiveness, or to create jobs (IRENA, 2014b). However, we should also consider job losses or job shift in other sector induced by PV development.

PV penetration perturbs the electricity market and it gives a negative impact on the national energy supply security (blackout cf. 3.2). First, the integration of non-dispatchable renewable technologies like PV affects the profitability of the producers who own the conventional electricity plants by reducing the wholesale price of electricity as well as their load factors. In addition, it would hinder the new investment of conventional power plants that operate as dispatchable back up capacities; this threats the national energy security in the long-term. Since this externality is directly related to energy security, more explanation is presented in the next section.

3.3.5 *Impact on the electricity mix & energy security*

The large integration of PV power in the energy mix gives important impacts on the existing electricity mix. It reduces the profitability of existing power plants, provoking the following issues;

1) Changes in the market price formation
2) De-optimization of the electricity mix

As explained in chapter 3.1.2, the capacities in the electricity market are ranked based on the ascending order of short-term marginal costs of production (merit order). PV production has zero marginal cost; the PV production has its priority on the electricity market. Accordingly, PV is ranked first in the merit order before base-load capacities. The merit order with conventional capacities is shifted to the right. The electricity demand is inelastic; the price variability does not change much the consumption. Therefore, with the same demand curve, the electricity price is reduced.

This is shown on **Figure 27**. Before PV integration, the capacity D was the marginal capacity during high demand period (Dt2), and the capacity B was the marginal capacity during low demand period (Dt1). However, with PV integration with no variable cost, the PV production shifts the merit order on the right (see **Figure 34**) (Commissariat Général à la Stratégie et la Prospective (CGSP), 2014).

Compared to **Figure 27**, on **Figure 34**, the average electricity price is reduced to *Pt*1* from Pt1 with the demand Dt1, and to Pt2* from Pt2 with the demand Dt2. In terms of temporarily reduced demand, it is sometime technically too difficult to shut down a capacity. In extreme cases, the market price can be negative. Consequently, the capacity D is not in use even though it exits in the market. In addition, revenues of other dispatchable capacities are reduced because of change in market mechanisms with PV integration.

In the long-term perspective, the profitability of existing plants is reduced and some producers have difficulties to recoup the investment. Moreover, investors are reluctant to build conventional plants because of the uncertainty of redeem of capital invested; this creates threats on energy supply security.

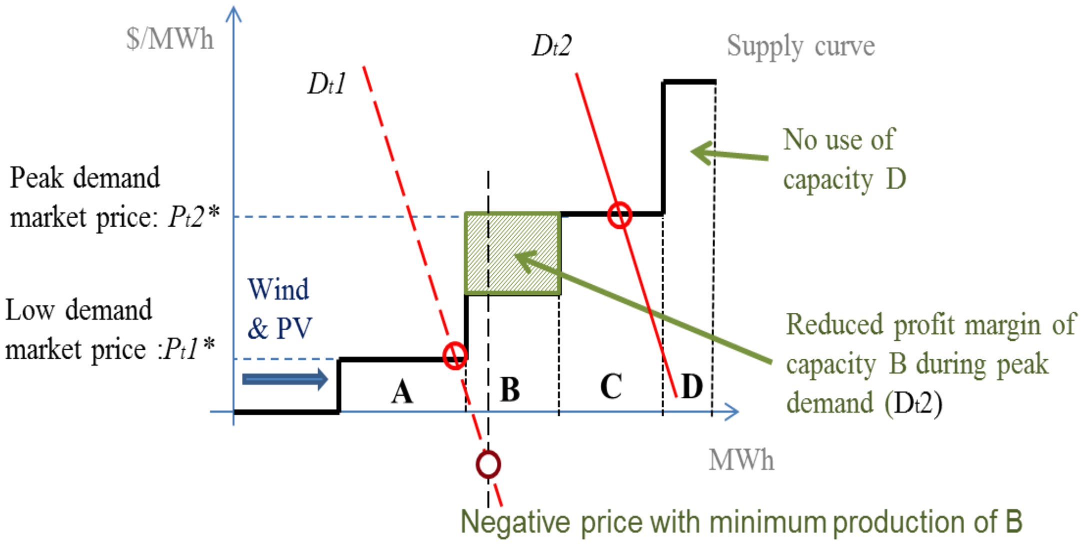


Figure 34: Merit order shifts with the integration of intermittent power (e.g. PV)

The penetration of renewable energies sources like wind and PV induces a sub-optimization of the current electricity mix; it reduces conventional power plant's operation hours and their load factors. At a high penetration of PV power, the load duration curve would be significantly shifted down; this leads to change in the electricity mix. This would increase a problem in terms of future investment choice; investors would less prefer the investment, which requires high fixed costs. Solutions (e.g. capacity payments) should be prepared to address this issue to maintain the energy supply security.

4 Conclusions

This chapter presented the state of the art analysis of PV technology. The silicon technology dominates the current market accounting for around 90% of the global PV market. However, other technologies exist; some technologies such as thin film are already mature and more suitable in certain areas with advantages, e.g. low manufacturing costs (CdTe), low production cost and better yield (a-Si), and more appropriate usages of building integration (transparent thin films). Other technologies become more mature (e.g. concentration PV (CPV), organic PV, dye sensitized PV, etc.). However, these technologies have not been able to compete with silicon technology whose prices have fallen sharply over the last decade due to economies of scale. Indeed, the silicon technology has benefited from the global experience curve effect (the costs decrease as the cumulative production increases) and this led to a lock-in phenomenon in the PV market. There are fewer incentives to make a long-term investment to establish the market for other technologies

This chapter has also shown that the decline in PV system prices is no longer solely associated with the decline in PV module prices. We found that significant margins exist for further reduction in decentralized PV system costs; it can be through non-module sectors called 'BOS (balance of system)'.

In this chapter, it was highlighted the intermittency of PV generation raises many questions about the large-scale integration of PV power into electricity system. It was then necessary to integrate the concept of **systemic costs,** which notably include additional costs to integrate PV energy into the network (grid-level costs) and to ensure its stability in the energy mix (balancing and back up costs). These additional costs could be solved with the large-scale electricity storage solutions, but these are not accessible in the short or medium term in most regions. However, our study highlighted the fact that the rapid decline in the cost of Li-ion batteries opens up new prospects in terms of PV integration in the medium term. They can be easily combined with PV systems, particularly with decentralized PV systems.

Based on all the information, we conducted an analysis using a SWOT methodology to study PV usages (off-grid, grid-connected distributed and grid-connected centralized). The ultimate goal of this analysis is to help policymakers to draw the best PV development strategy for each usage. We found the following points;

1) Off-grid PV systems have great potential to supply electricity for sunny rural areas or remote regions without network. It can also be used for areas with the grid connection, but with low reliability of power supply due to grid problem. Many developing countries with energy poverty problem represent an important potential market (over 1.3 billion people in the world are still without access to electricity). In this case, the intermittency of PV power is the big obstacle to solve and the use of battery is necessary. The development of this usage is very sensitive to the fossil fuel prices (substitute).
2) Grid-connected distributed PV systems have more stable power supply thanks to the grid. Opportunities exist related to positive energy buildings under low carbon policies or desire of energy independence. However, they are penalized by their costs and their impacts on the

network. The best strategies for this usage can be proposed by addressing those issues. The further cost reduction can be possible by targeting the part of 'BOS'. Technical possibilities exist to limit the impacts on the network (e.g. matching PV system output and demand profile, demand response, local storage, smoothing via geographic spread and so on.). In this regard, our study introduced the notion of self-consumption. This will be further discussed in Part III.

3) Grid-connected centralized PV systems are penalized by the intermittent PV production (non-dispatchable) with an important impact on the network. They cause PV systemic costs in the electricity system and reduce the PV competitiveness in the energy mix. In order to minimize the impacts, we recommended the optimal use by targeting sunny regions where the electricity consumption best matches with the PV system output. In addition, they are also sensitive to the reduction of fossil energy costs because they compete with conventional technologies in the electricity market. In addition, the costs of land usage and land availability should be considered to develop these systems.

As described, impacts on the network are central issues for grid-connected systems. In this chapter, we have shown PV integration's impacts on the network management and electricity market, in particularly related to the large-scale integration of PV power. It reduces the time of use for certain plants that are needed to balance the network and lowers the wholesale prices of electricity. This affects the profitability of conventional power plants. In this regard, the detailed breakdown of possible systemic costs (additional integration costs) was presented based on the concept of grid extension and upgrading, short-term balancing and long-term back-up. In addition, both positive and negative externalities, which have not been internalized in the PV system costs, were also discussed in this study. Therefore, the impacts on conventional power generators and grid operators are necessary to review prior to the political decision of PV integration in the energy system. This will be further discussed in Part III.

Chapter 3. Role of public policies for the development of PV energy

The role of policy in the development of PV is discussed in the chapter 3. This chapter first discusses the major international environmental objectives which largely motivate the developments of renewable energy. As shown in the previous chapters, the development of the PV is limited without political framework. PV technology still lacks competitiveness and the intermittency of PV large scale production can greatly affect the national electrical power system. In this context, the chapter leads to the scenarios proposed by the IEA, which give basic guidance to the domain, as well as associated general policy recommendations.

As seen, in the previous chapters, a complete assessment of the PV field is presented containing PV technologies, economic and systemic analysis, and an overview of its likely future evolution. All these elements allow us to conclude the chapter with a risk analysis of the development of photovoltaic energy in the energy system. Accordingly, we present the risks and the most important challenges which need to be taken into account for the development of PV. All of these elements will be used as a theoretical framework for the study in the following Parts.

1 Policy objectives and related policies

The environmental benefits and a shift towards a sustainable energy system are important driving forces to deploy solar PV power in the current or future energy system. In this section, the political efforts and movement in the development of PV are studied, with a focus on IEA scenario.

1.1 Objectives of international policy and European policy (2020, 2030, 2050)

Over the past decades, climate change has been a subject of serious international negotiations, along with the growing concerns on the environment (IPCC, 1990). The international community has been working together to reduce the greenhouse gas (GHG) emissions that cause climate change. The Intergovernmental Panel on Climate Change (IPCC) was set up in 1988 to provide scientific assessment on climate change. Scientific evidences suggested that the GHG emissions need to be deeply reduced to limit the global warming below 2°C by 2100 compared to the temperature in pre-industrial times in order to prevent severe climate change problems; the de-carbonization of energy system with the utilization of renewable energies is highlighted as one of the feasible tools to reduce the GHG emissions (UNFCCC).

The United Nations Framework Convention on Climate Change (UNFCCC, 1988) is the leading intergovernmental treaty that addresses the climate change problem. The 1992 UN Conference on Environment and Development (UNCED, the Rio Earth Summit) is the first multilateral international environmental agreement to fight climate change based on the precautionary principal[44]. It focused on collective interests requesting present acts to prevent tomorrow's risks. The economist's intertemporal analysis between today's costs and future benefits are often used to discuss about the

[44] Principal 15: 'where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation'; the PP is also taken by European Community in article 174 of the EC treaty (IPCC).

precautionary principle (Arrow, et al., 2012; Immordino, 2003). The UNFCCC entered into force on March 1994 and it has been ratified by 195 countries. The UNFCCC suggest common but differentiated responsibilities among member countries. However, it did not give specific quantitative objectives.

The Kyoto Protocol[45]suggested a legally binding obligation to member countries to reduce GHGs. The Kyoto Protocol obliges Annex I countries to cut their emissions of GHG by at least about 5% for the period 2008-2012 compared with 1990 levels (United Nations, 1998); the second commitment period started from on 1 January 2013 and will end in 2020. The Kyoto mechanisms also presented three economic instruments; Emissions Trading, the Clean Development Mechanism (CDM) and Joint Implementation (JI).

The 21st Conference of the Parties to the 1992 UNFCCC (COP 21, 2015 Paris Climate Conference) and the 11th session of the Meeting of the Parties to the 1997 Kyoto Protocol (CMP11) have been held in Paris in November and December to decide on a post-2020 regime. The 2015 Paris Climate Conference achieved international agreement on climate change with the objective of limiting global warming below 2°C compared to pre-industrial levels by 2100 (UNFCCC). This will take effect from 2020 as a replacement of the Kyoto Protocol (European Commission, 2016). It also includes $ 100 billion per year in climate finance to support the developing countries by 2020 and this commitment will be further increased in the future.

Prior to the conference, many countries presented the GHG emission reduction targets. The US and China jointly agreed to limit GHG emissions in November 2014. The US set a goal of reducing its emissions by 26%-28% from 2005 levels by 2025. China intends to achieve the peaking of CO_2 emissions around 2030. In addition, China will increase the share of non-fossil fuels to 20% in the national energy mix by 2030 (The White House, 2014; Climate action tracker, 2015). Japan has confirmed a plan to reduce the GHG emissions by 26% by 2030 from 2013 level (Nikkey Asian Review, 2015).

The European Union (EU) demonstrated the leading position towards combating climate change. The European climate and energy package proposed targets for 2020 to realize a highly energy-efficient and low carbon economy[46]. Three key objectives for 2020 (the 20-20-20 targets (European Commission, 2016b)) are presented as below.

- a 20% reduction in EU GHG emissions from 1990 level
- an increase of the share of EU energy consumption produced from renewable energy resources to 20% (at least 10% of the transport fuels should come from renewable sources by 2020)
- a 20% improvement in the EU's energy efficiency

Those targets are decided as EU directives, which means they must achieved in every member states. National authorities have to adapt their laws to achieve those objectives; however, they are free to decide how to meet such goals. In the national action plans, each member country explains how they intend to deliver them.

[45] Kyoto Protocol was first agreed in December 1997 and it was entered into force in Februry 2005.
[46] The targets were set by EU leaders in March 2007 and were enacted in 2009.

The European strong political intention was expanded for the period up to 2030 and 2050. In 2014, EU leaders agreed to reduce the GHG emissions by at least 40% lower than 1990 level by 2030, to increase the share of renewable energy to at least 27% and to improve the energy efficiency by at least 27% by 2030 (European Commission, 2016c). The European Council, however, endorsed an indicative target of 27% to be reviewed in 2020 having in mind a 30% target. In addition, the European Union suggested bigger climate efforts aiming the reduction of GHG emissions to 80% below 1990 level by 2050 (European Commission, 2016d).

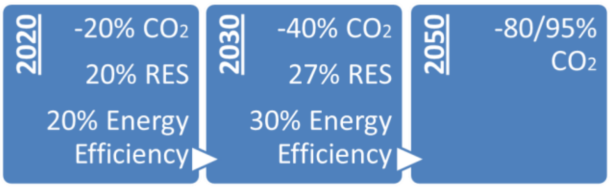


Figure 35 : European Union's energy policy objectives below 1990 level (roadmap for 2020-2030-2050) (ENTSOE, 2015, May 19-22)

The 2050 EU's roadmap suggests a movement to a low-carbon economy. The GHG emission reduction efforts should divided cost-effectively between the main emitting sectors, power generation, industry, transport, building, agriculture and construction. For example, ***Power sector*** has the biggest potential for cutting emissions; EU's roadmap suggest a total elimination of CO_2 emission from this sector by 2050. It can be possible from electricity generation using renewable sources like wind, solar and biomass, or low carbon energies like nuclear power plants, or fossil fuel power stations equipped with carbon capture and storage technology. The share of these low carbon technologies in power sector will be increase to around 60% in 2030 and to almost 100% in 2050 from 45% today (Roadmap 2050). In addition, the GHG emissions in ***transport sector*** are still growing. According to EU's 2050 roadmap, it can be reduced to more than 60% less than 1990 level by 2050. The shift to plug-in hybrid cars and electric cars after 2025 will allow sharply reducing the emission of GHG in this sector. Furthermore, the emissions from the ***building sector*** will be nearly removed by 2050; the energy use in this sector will be largely powered from renewable energies and the investment can be covered through reduced energy bills.

1.2 Perspectives of international organizations and proposed policy actions

Various international organizations published the roadmaps to increase renewable energies in order to address the global climate change issues. Among those reports, solar PV energy is mostly highlighted to deliver such objective. For example, according to IRENA's Remap 2030, the installed capacity of PV power will reach 1250 GW by 2030 (IRENA, 2014c). EPIA's scenarios projected solar power will contribute to between 10% (low scenario) and 15% (high scenario) of Europe's electricity demand by 2030 (EPIA, 2014). In addition, according to IEA's reports, 16% of the global electricity will be supplied by solar PV power by 2050. This study attempts to take a close look at the IEA scenario, which suggests an elaborated vision with specific political action plans.

❖ **IEA vision: 2014 Energy Technology Perspectives**

1) Objectives of utilization of PV energy in the energy mix

The IEA's perspective suggested that GHG emissions reduction target can be delivered through increased share of renewable energies in energy mix, in particular using the photovoltaic (PV) energy. In the IEA's Energy Technology Perspectives (ETP) report, the 2°C Scenario by 2100 (2DS) proposed a radical energy system transformation to achieve the goal of limiting the global mean temperature increase to 2°C. The 2DS is largely consistent with the IEA's World Energy Outlook (WEO) 450 Scenario (IEA(b)).

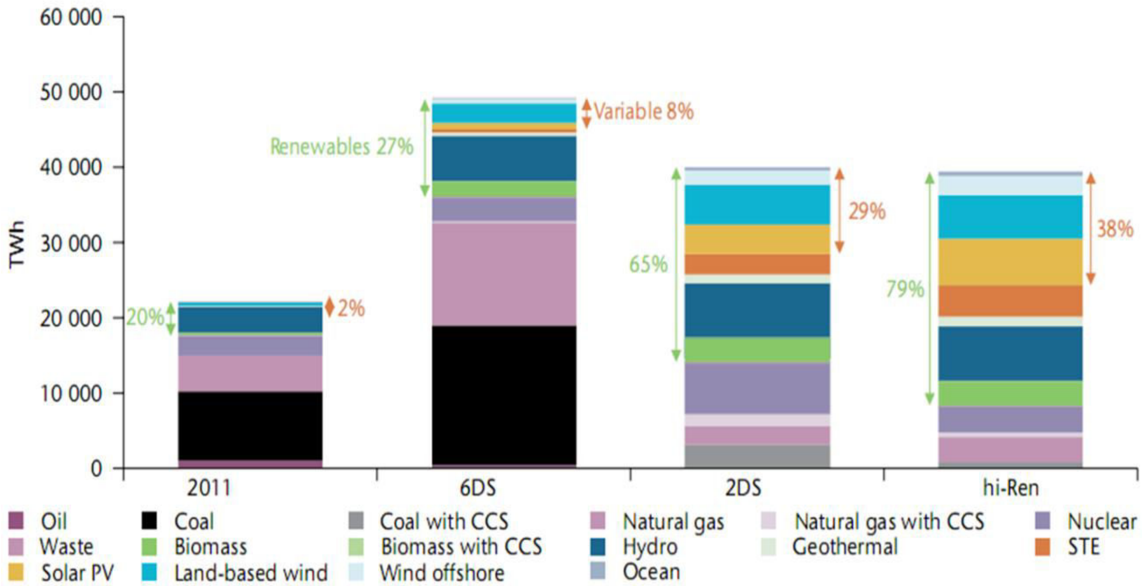


Figure 36 : IEA's global electricity mix in 2050 (IEA, 2014)[47]

IEA's 6DS scenario assumes that the current trends continue (see **Figure 36**). However, renewable energies dominate the global electricity supply in the 2DS (65%) and the hi-Renewables scenario (hi-Ren) (79%) by 2050. Variable renewables provide 29% in the 2 DS and 38% in the hi-Ren. The increase of flexibility of electricity mix using variable renewable energies is important to secure the stable supply of electricity in these scenarios. Gas plants that run with relatively low full-load hours are mainly considered to balance generation from variable renewable sources; e.g. only 7% of electricity is produced in fossil power plants without CCS in the 2 DS (IEA, 2015, pp. 38-39). In addition, dispatchable low-carbon technologies (solar thermal, electricity (STE), biomass or geothermal plants) are also considered for that.

The IEA's ETP 2014 (IEA, 2014b) report predicts, based on hi-Renewables scenario (hi-Ren) model, [48]16% of world's electricity will be supplied using PV energies by 2050, which means the

[47] 6DS is a base-case scenario on the condition that the current trends continue. It projects that energy demand would increase by more than two-thirds between 2011 and 2050. Associated CO_2 emissions would rise even more rapidly, pushing the global mean temperature up by 6°C. The 6DS is broadly consistent with the World Energy Outlook Current Policy Scenario through 2035.

installed PV capacity will achieve 4,674 GW in 2050. This scenario is a variant of the 2DS model, assuming a slower deployment of nuclear and delayed introduction of carbon capture and storage (CCS) technologies, and more rapid deployment of renewables (79%), notably solar and wind energies.

In this case, solar PV will generate 6 300 TWh of electricity in 2050 and the annual emissions of carbon dioxide (CO_2) up to 4 gigatonnes (Gt) will be avoided. Table XV illustrates the IEA's solar PV goals for 2030 and 2050.

hi-Ren scenario	2013	2030	2050
Installed PV capacity	135 GW	1721 GW	4674 GW
PV electricity generation	160 TWh	2370 TWh	6300 TWh

Table XV: IEA's solar PV goals for 2030 and 2050

IEA estimates that China will take the lead in developing the PV growth by 2050, accounting for around 35% of the world PV electricity production. In contrast, Europe's share is expected to decrease to less than 4% by 2050.

Year	US	Other OECD Americas	EU	Other OECD	China	India	Africa	Middle east	Other developing Asia	Easter Europe and former Soviet Union	Non-OECD Americas	World
2013	12.5	1.3	78	18	18	2.3	0.3	0.1	1.4	3	0.2	135
2030	246	29	192	157	634	142	85	94	93	12	38	1721
2050	599	62	229	292	1738	575	169	268	526	67	149	4674

Table XVI: IEA's estimation of PV capacities by region under the hi-Ren scenario (unit: GW)

In the hi-Ren scenarios, the share of PV contribution in the national electricity mix varies according to solar resources and electricity load; 18% in the US, 21% in China, 8% in EU, 22% in India, 11% in Africa, and 18% in the Middle East regions. The future PV use is mainly based on grid-connected system (98%) and the rest is off-grid systems (2%). The market segment is indicated in **Figure 37**.

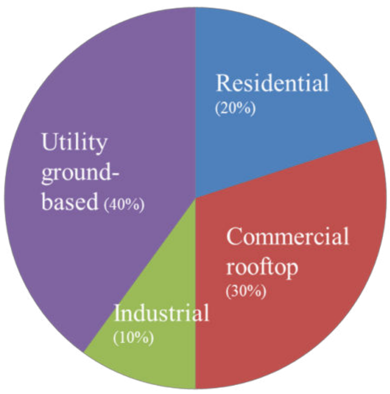


Figure 37: Market segment of PV in the hi-Ren scenario

[48] IEA scenarios look into various technology solutions that can contribute to limit climate change to 2°C: e.g. improvement of energy efficiency, increase of the share of renewable energies, expanded nuclear power and CCS technologies.

The IEA's ETP model asserts that the improvement of technology performance and the reduction of PV costs are necessary to increase the competitiveness of solar PV energy for the rapid penetration of solar PV energy in the future energy mix. The module costs are expected to fall to US$ 0.3/Wp to US$ 0.4/Wp by 2035. As the technology improves, the PV system prices for both utility-scale and rooftop PV systems will converge towards the lowest levels; average costs for utility scale plants will reach a level of US$700/kWp by 2050 and the average rooftop PV system costs will be around US$1000/kWp by 2050. However, the soft costs would remain high. The IEA's ETP report also assumes that the average LCOE will continue to reduce by narrowing the country gap. Table XVII indicates the average LCOE for utility scale PV plants and rooftop PV systems.

hi-Ren scenario	2013	2030	2050
Average LCOE for utility-scale PV plant (US$/MWh)	177	81	56
Average LCOE for rooftop PV systems (US$/MWh)	201	102	78

Table XVII : IEA's estimation of the PV LCOE in hi-Ren scenario

As the most global market would share a similar PV system prices in the future, the costs of capital will have a greater role for calculating LCOE of PV power in the future. For example, it defines that when the weighted average capital cost (WACC) exceeds 9%, more than half the LCOE comes from the financing.

The de-carbonization of the entire energy system by 2050 in the 2DS will require about US$ 44 trillion of additional spending. This investment is more than offset by over US$ 115 trillion in fuel savings, resulting in net savings of US$ 71 trillion. Even with a 10% discount rate, the net savings are more than US$ 5 trillion (IEA, 2014b).

Furthermore, apart from the use of back up energies, IEA report also suggests other various methods to increase flexibility of electricity mix that contains a high share of variable renewable energies like solar.

- Electricity storage
- Larger balancing area using transmission lines or interconnection
- Other parts of the system as flexibility assets
- Demand response measures (e.g. smart charging of EVs)
- Linking the electricity system with the heat system
- Linking the electricity system with fuel production (such as electrolysis of hydrogen)

In the following, we discuss IEA's policy recommendations with the objective to realize the PV presented objectives.

2) IEA's recommended policy actions to achieve those objectives

Deploying PV power according to the vision of this roadmap requires consistent and balanced policy support. In order to achieve the proposed targets of PV power generation, IEA recommends various policy actions in four main areas;

a) ***Establish medium & long-term targets for PV deployment*** in line with the national energy strategy and the country's mitigation efforts to combat climate change.

b) ***Prepare stable and long-term predictable financial support mechanisms*** to stimulate PV system deployment: stable legal frameworks are needed in line with support to minimize investors' risks and reduce capital costs.

- Possible financial support mechanisms for utility-scale plants: FITs, auctions for long-term PPAs
- Facilitate distributed PV generation either using FITs[49] or net metering

c) ***Reduce PV costs*** through technology improvement mainly driven by industry or via reducing 'soft-costs'.

d) ***Anticipate the deployment of variable PV generation*** through evolution of transmission and distribution grids and the rest of the electricity systems to ensure the security of supply.

Establish medium & long-term targets for PV deployment	Prepare stable and long-term predictable financial support mechanisms
Decrease PV costs through technology improvement or via reducing "soft-cost"	Anticipate the deployment of variable PV generation through evolution of transmission and distribution grids, and the rest of the electricity systems

Table XVIII: IEA's recommendations to achieve the targets of PV power generation

IEA's roadmap also highlights the importance of addressing existing and potential barriers that hinder the development of PV energy. The removal of ***non-economic barriers*** enables to reduce administrative and transaction costs (Coase, 1937). For example, the following actions are recommended to increase the competitiveness of PV power.

- Streamline the PII (permitting, interconnection, and inspection) process to reduce bureaucratic administrative process, unnecessary costs, and waiting time.
- Prepare training and certificate systems for PV installers.
- Prepare internationally recognized standards for PV modules and systems in various climatic conditions.

[49] This roadmap recommends that FITs have degressive rates and quantitative limitations.

In addition, it is important to increase the flexibility of the existing power system to facilitate the large penetration of PV system in electricity mix. The following actions will help increase the flexibility.

- Reduce the costs of decentralized electricity storage.
- Prepare demand-side response and effective storage options.
- PV system can be installed directly on consumption sites.

The international collaborations will bring various advantages in terms of PV deployment. It allows the national PV energy actors to look for synergies (knowledge, experiences, and infrastructures) in terms of PV development activities. The long-term harmonization of PV energy research can be thought. Furthermore, the standardization in terms of grid integration can be implemented for the better integration of PV power. It can also help provide with best practices in developing countries for the large deployment of PV electricity in the future energy mix.

Along with the increase of self-consumption in the future, there will be raising concerns regarding the fair recovery of fixed costs of grids. A continuous effort to monitor the impacts of large penetration of PV systems in the existing distribution network is needed.

2 Risk analysis of PV development

Despite such progress, photovoltaic energy has a various risks and challenges to become a major electric energy source in the globe. The observed rapid growth was mainly led by policy support and there is still room for improvement of PV's natural outgrowth without those political favors. It is thus important to identify barriers, which hinder the development and utilization of solar PV energy to enhance PV's competitiveness in the electricity mix. An accurate picture of PV risks and challenges facilitates to map out a future for PV development and utilization (Hämäläinen & Karjalainen, 1992).

This section attempts to define key barriers associated with PV growth according to multi-angles (Abu-Taha & Daim, 2013): technological, market, institutional (political change), financial risks (uncertainty to meet the target costs), supply risks and context risks (Popiolek, 2015, p. Ch. 4.IV; European Commission, 2010)

The analysis to identify a range of risks and barriers for PV electricity growth is based on existing literatures (Painuly, 2001), expert opinions, and personal judgments. In order to give a precise outlook of risks, the nature of risks, cause or sources of risks and potential consequences of risk occurrence are defined for each range of risks (European Union, Op. cit.).

2.1 Internal risks: direct risks (or rupture) related to PV evolution

The internal risks are the risks inherent to the photovoltaic sector. They include the risks associated with the technologies of the PV system (e.g. solar PV cells and storage system) and PV market needs (PV usage), and the risks related to the organizational aspect (e.g., institution or financing).

2.1.1 *Technological risks (supply-side)*

PV technological risks are all those that arise associated with technical issues (e.g. module, non-modules devices, installation or engineering works, and system integration) or possible technical breakthroughs. PV energy has experienced an impressive technological shift. PV is now a mature and proven technology (UK's Department of Energy & Climate Change, 2013). PV systems generally produce small amounts of electricity (few kW to few MW) and need no fuel. PV electricity thus presents few technological risks compared with other energy technologies. Different technological risks and challenges are captured in Table XIX according to PV value chain. The risks related to raw material supply are defined in the next part.

Risk	**Cause / source**	**Potential consequences**
Solar PV cell/module performance (IEA, 2014)	R&D for PV cell efficiency [50] Manufacturing & experience Material amount used to make PV modules	PV Market lock-in by c-Si technologies Change in PV module prices Technological breakthroughs (c-Si→ non c-Si technologies)
BOS performance (Timilsina, et al., 2012) (mainly compared to module performance)	Lifespan of BOS components Efficiency of non-module PV equipment (e.g. inverter)	Increase PV O&M costs Change in PV system prices
Batteries performance	R&D in batteries (lifespan, recycling..) Breakthrough of batteries technologies Market development (cost reduction)	Influence PV system costs Synergies for PV growth (acceleration of PV usage development) Reduce risks associated with the intermittency of PV power
PV integration in electric power system (Intermittency of PV production)	Grid connection Grid quality variation Characteristics of electricity mix (flexible capacity) Lack of storage system solution	Influence the grid management Negative prices Affect the energy security (e.g. blackout)

Table XIX: PV technological risks

Among identified risks, a few points should be focused.

1) **Possible technological breakthroughs that induce a drop in PV system price**

These give significant impacts on PV development. They can be realized led by dynamic R&D activities, innovations or further development of non c-Si technologies like thin film; the technology lock-in problem by c-Si should be solved to bring technological breakthroughs to advance non c-si technologies.

Furthermore, breakthroughs related to BOS also reduce the PV system prices. In fact, the costs of BOS are not always declining proportional to the decline in module price in the current PV system (World Bank 2012). The improved BOS performance or innovative approach to reduce BOS costs are feasible in the short-run through R&D efforts and process improvement.

2) **Possible breakthroughs of storage solutions (e.g. batteries) to solve the PV intermittency**

A low-cost energy storage solution would give a good solution for the large deployment of the intermittency PV electricity. When the combined PV and battery system is provided at a reasonably cheap price, the large penetration of PV electricity would be more feasible; it would expand the realm

[50] C-Si: cell efficiency and effectiveness of resources consumption through materials reduction, improved cell concepts, and automation of manufacturing (IEA, 2014)
Thin film: cell efficiency, experiences in manufacturing and market, and long-term reliability

of PV self-consumption. Moreover, the large storage system would reduce the grid-level costs of PV electricity.

3) Risks related to PV integration

When the PV power accounts for a large share in the electricity mix, risks concerning PV integration became significant. Sometimes, the integration of PV in the energy system stimulates some problematics like negative prices. The management of the variability of PV production is very essential to reduce PV integration risks. Therefore, a well-adjusted technologies or practices to integrate PV electricity are needed to reduce such risks. In addition, smart strategies of PV deployment to minimize the systemic effects on the electricity system can be also considered.

2.1.2 Market risks (demand-side)

Market risks are related to market disappearance or appearance; the acceptability of consumers (uptake of new or changed products or services related PV systems) is the key element to make or break the market. Market risks occur when the market cannot justify the investments. The market acceptance can be improved through effective communication or public campaigns.

Unexpected market development based on an innovative concept of PV usage gives a quantum leap of PV. In addition, PV-related market development gives a positive impact on PV development; e.g., the residential PV system can get a benefit from the development of Li-ion battery.

Risk	**Cause / source**	**Potential consequences**
Market acceptance for PV	Preference on solar PV energy or vice versa Complexity of usage (PV system) Price of PV system	Expand or decline PV installations
Unexpected market/PV usage	Innovation in PV usage e.g. coupling with other sector (EV)	Expand the scope of PV application & increase PV installations
Market development associated with PV (e.g. batteries)	Innovation in PV- related sectors (e.g. batteries)	Synergies of PV development (e.g. combined PV system with batteries)

Table XX: PV market risks

2.1.3 Institutional risks

PV institutional risks are all those risks of failing or under-delivering due to the characteristics of organizational institutions. The successful development of PV energy requires effective institutional devices. For example, appropriate laws should be prepared to encourage a wider utilization of solar PV energy as well as to prepare supporting infrastructures. The major institutional PV risks are presented in Table XXI.

Risk	Cause / source	Potential consequences
Institutional risks	Lack of appropriate legal/regulatory framework	Discourage the PV use Reduce investment in PV Increase costs/ time to install PV system
	Lack of professional institutions (limited understanding among key national and local institutions to develop PV)	
	Lacks of public education or training systems	
	Complicated and time consuming procedural problem	
PV political risks	Policy inconsistency A stop-go political cycle	Interruption of PV development
Conflict of interests among stakeholders	Lobbying against PV growth from conventional energy industry or grid operators Lack of dialogue among stakeholders	Interruption of PV development
Social feasibility risks	Land usage Esthetic aspect	Interruption of PV development (or develop niche market)

Table XXI: PV institutional risks

The institutional role is very important for PV growth since the political strategic direction has played a crucial role for it. Most institutional risks are directly related to the present PV policy designs. Three points should be focused:

1) **Organizational (institutional) barriers that increase PV costs**

Some organizational barriers cause unnecessary costs and a time lag. For example, an inefficient administrative process or untrained workers delay PV project implementation requiring additional costs. In addition, a change in electricity market mechanisms can influence the PV development when the PV is integrated in the electricity market. Targeted policies can reduce those risks.

2) **The consistency in the PV policy**

Another important risk is related to the **lack of continuity of PV policy** in the medium-to-long-term. Frequent shifts in PV policy or policy incoherence confuse investors who need a long-term perspective to secure their investments (Negro, et al., 2010). A clear and credible long-term policy signal is important for the development of PV (IEA, 2014).

3) **Conflict of interests among stakeholders**

There are some hidden risks concerning the conflict of interest among stakeholders in the national energy market. The **lobbying against PV** can discourage ambitious PV policy (Energy and Policy Institute, 2014). Therefore, such risks caused by traditional energy firms or grid operators cannot be ignored. It is important to have a communication or preparatory meetings among such stakeholders to reach an agreement. For example, a fair system to recover fixed costs of grids with PV integration or a solution to missing money issue can be handled under this context.

4) **Social feasibility**

It is important to increase **social feasibility** of PV power in the electricity system. The land usage is important issue related to PV development. As seen in chapter 2, this can be a threat for utility-scale PV plants: the opportunities cost of lad usage should be considered. However, PV has a good social feasibility compared with other energy source like wind power (Senat, 17th February 2015).

2.1.4 *Financial risks*

The financial risks represent uncertainty to meet target costs or the ability to secure the funds needed. PV energy has economic advantages due to its lower fuel and operating costs. However, there are several financial barriers in terms of **high initial investment, lack of easy financing, high system costs**, especially, related to integration of electric power system.

The investment choice is evaluated based on experiences of PV development, economies of scale and other factors such as energy prices. However, reflecting its shorter history compared to other conventional energy sources, PV is assessed in the high-risk group of projects with high transaction costs by financial institutions at higher interest rate. Furthermore, PV has a high system price compared to conventional energy sources. The major financial risks are summarized as below;

Risk	Cause / source	Potential consequences
Lack of access to capital / credit	Poverty (high in developing countries) Lack of confidence of funders	Impossibility to buy PV systems
High discount rate / High cost of capital	Lack of confidence in PV technology and policy	Increase PV LCOE Discourage investment in PV
Forecasting error in PV prices	Rapid & diverse change in the PV sector [51] & incomplete information	Financial burden, market collapse

Table XXII: PV financial risks

The following points represent the major financial barriers.

1) **Lack of capital to install PV system**

This barrier is related to funders' confidence in PV projects. This occurs more often in developing countries.

2) **Cost of capital**

PV development is capital-intensive and a low capital cost is a plus for PV deployment growth52. The investment in PV projects is very sensitive to the policy; a strong and consistent policy signal is need to attract more capital in the PV sector (Ardani et al. 2013). The interest paid on both debt and equity has a significant impact on the total cost of a large-scale photovoltaic project. The cost of capital is and will remain a major driver for the cost of PV power (Fraunhofer ISE, 2015b).

3) **Forecasting error in PV prices**

The difficulties of forecast of PV prices bring another barrier for PV devolvement. **Forecasting error** is an important issue for the policy planner. In the current PV market, the national PV system price is much influenced by the global market situation. The incomplete information is a challenge for the PV policy design. Such forecast errors can lead to financial burdens or a market collapse. This risk is highly correlated with breakthroughs of other sectors like technology or market.

[51] Example with FIT in Spain, France, Germany, and Japan.
[52] Almost all expenditure are made up-front (IEA, 2014)

2.2 External risks: indirect risks (or rupture) on PV growth

The external risks are the risks induced by the relationship of the PV sector with other sectors of the economy. It includes the risks associated with the raw material supply and those related to the external environmental factors for PV growth.

2.2.1 Supply risks

Raw material supply risks give constrains of PV growth. Some PV technologies like c-Si, CdTe, and CIGS have supply risks of raw materials.

The supply of PV-grade silicon for c-Si technologies was interrupted in the mid-2000s giving negative impacts on PV market growth. In addition, the supply of Cadmium and Tellurium is related with the certain thin film technologies. Their availability depends on the industry evolution of zinc mining and copper processing respectively. Material intensity needs to be reduced for large-scale PV deployment.

Risk	**Cause / source**	**Potential consequences**
Raw material supply risks (scarcity) (Kavlak, et al., 2015) : stable supply & availability of raw materials	PV-grade silicon for c-Si technologies Indium for CIGS Stable supply & availability of Cadmium and Tellurium for CdTe [53]	Increase the module price Disruption of PV growth Industry crisis by excessive supply
Health	Cadmium (CdTe)	Reduce the use of CdTe

Table XXIII: PV supply risks (raw materials supply)

The most important risk is the scarcity of some raw materials like indium (CIGS). The supply risk threatens some PV industry technologies (thin film), but not the whole PV sector; different materials are used for other PV technologies. Conversely, the supply risks can also include the oversupply of raw materials issues which eventually leads to the industry crisis (e.g. oversupply of polysilicon).

2.2.2 Context risks

Context risks arise in case of a lack of stability in the policy environment. They are induced by external factors that the government cannot fully control. The major environmental risks of PV are captured in the Table XXIV.

Risk	**Cause / source**	**Potential consequences**
Substitutes risks e.g. (fossil fuel prices)	Unexpected change in competing energy technologies or price (e.g., coal, oil, shale gas, shale oil)	Reduce PV competitiveness
Economic situation	Rapid economic growth Economic crisis	Increase or reduce energy demand Influence the development of renewable energies (incl. PV)
Globalization (international trade)	Free trade zone Trade barriers	Influence PV system prices & PV industry

Table XXIV: PV context risks

[53] By-products from respectively the zinc mining and copper processing and their availability depends on the evolution of these industries

The following market risks are important to realize the large deployment of PV electricity.

1) Substitute risk (e.g. fossil fuel prices)

The substitute risk is important for PV growth. When the competing technology cost largely reduces, the development of PV would slow down. For example, a decreased fossil fuel prices can disturb the development of PV power; the exploitation of shale gas or shale oil gives an alternative solution of cheap energies for the future energy mix (Stevens, 2012). In this case, the PV electricity becomes less competitive compared to fossil fuel solutions.[54]

2) Economic situation

Economic situation is an important element in terms of PV devolvement. Energy demand is influenced by the economic condition. For example, rapid economic development increases energy consumption while an economic slowdown reduces the energy demand. Therefore, the national or global economy situation affects the PV development indirectly.

3) Globalization

The globalization influences the PV development because the current PV market operates under the open economy. As seen, the global market shares the similar PV module price and some countries implement trade barriers to protect their domestic market. This largely influences the PV industry.

3 Conclusions

This chapter has shown that international goals for combating climate change are ambitious along with the increasing awareness of environmental issues. IEA's hi-Renewables scenario suggests a very important pathway of photovoltaic energy development; installed PV capacity will reach 4,674 GW by 2050 (this means that solar PV will generate 6 300 TWh of electricity in 2050). To achieve those objectives, IEA presents different inquiry themes to remove blockages of PV development with policy recommendations. Those subjects intersect with author's analysis. However, author's analysis provides a deeper insight into the PV system mechanisms and its dynamic features.

Referring to all defined information concerning the PV energy sector, this chapter concluded with a discussion on risks of PV development according to author's analysis. They have been classified according to six areas: technological, market, institutional, financial, supply, and contextual risks. There are few technological risks; however, a 'breakthrough' of PV technologies or batteries possibly modifies the outlook for PV market in the future. It is the same with market risks. In addition, synergies between PV technology and market could accelerate the spread of PV energy.

The conducted risk analysis also defines the major institutional risks; they are related to the lack of institutional framework and the continuity of the PV policy. In addition, the conflict of interests among stakeholders should not be ignored; this issue will be further discussed in Part III. Financial risks concerning the development of PV also exist related to the investment cost and the cost of capital; these factors can limit the diffusion of PV in developing countries. The PV market is sometimes

[54] If no carbon price is implemented.

largely subsidized. Therefore, risks exist related to forecast for PV price evolution; the forecast errors can block the national market growth or create market bubbles. This will be further discussed in Part II.

We have also defined supply risks related to raw material supply for certain technologies. Concerning contextual risks, economy situations and globalization of PV market are important elements to consider. Globalization impacts are discussed in Part II and Part III.

Like this, the analysis of overall risks of PV development is important to conduct in order to avoid any medium or high potential negative consequences of PV policies. These risks can be removed by benchmarking best practices.

Conclusions of Part I

In this Part I, we have developed the thesis subject methodically by specifying the context according to three axes defined in the subject title: **public policies, PV technologies and PV usages with their integration in the energy system**. This Part allows us to define the full context of the field of PV containing the different types of PV technology, PV usages, its obstacles, and public policies that lead to its development.

Based on the history of economic thought, the first chapter has specified the important role of public policies to support energy transition. The development of PV energy is beneficial to the society by reducing CO_2 emissions, providing a new engine for economic development through a sustainable energy system model (green growth) and improving energy security via diversification of energy sources. However, the motive of the private sector does not necessarily coincide with these objectives because PV energy are not yet competitive enough in the energy system compared with conventional energies and they include various risks and challenges. The state intervention is thus needed to realize such objectives; it relies on either production support through research or innovation in companies or indirectly through supporting demand.

The state of the art analysis of PV technologies is useful to understand the possible options of PV technology solutions and the market situations. PV has various solutions in terms of technology perspective. However, the current PV market is largely dominated by silicon technology. The established market has fewer incentives to make a long-term investment to develop other technologies than silicon technology (lock-in). Even though such technologies are more suitable in certain areas with advantages, the economic competitiveness is relatively weak compared to silicon technology that has largely reduced the cost due to the scale effects over the last decade. The commercialization barriers hinder to develop other technologies.

This chapter also presents the complexity of managing the electric power system that makes difficult to integrate intermittent PV energy in the electricity system as the massive electricity storage solutions for some hours or a season do not exist for the moment. It is therefore important to introduce the concept of systemic costs of PV that incorporates additional costs related to the network management, balancing and externalities.

Various PV usages have been implemented from PV technologies: off-grid and grid-connected (distributed and centralized). The SWOT analysis of PV usage enabled us to highlight opportunity and threats of each PV usage. Different strategy for each usage should be employed to find the optimal mode of PV power use in the electricity system. It should be discussed in terms of the political context and local situations since each country has different political context and conditions for PV development. The differences exist among regions in a country. Our SWOT analysis is useful to define the customized strategy of PV deployment by taking strong and weak points of each usage into account.

For example, if the aim is to reduce or minimize the systemic costs, we can deploy PV systems in areas with problems of grid-connection. In addition, we should avoid areas with overproduction of electricity. In addition, increasing the matching ratio between the PV power output and consumption is also important. Furthermore, if land usage and land availably matter, we can think about the strategy that can use the existing surfaces of buildings.

Finally, we reviewed the PV development opportunities in the context of energy transition from European objectives and the global scenarios of IEA (16% of global electricity from PV by 2050, this means that installed PV capacity will achieve 4,674 GW in 2050). We also gave a brief review on IEA's policy recommendations to achieve those objectives. Our study on PV policies somehow intersects with the IEA's perspective. However, our study also analyses the mechanisms behind and the dynamics of PV policy system based on a systemic perspective.

All these elements helped us finish this Part with a risk analysis related to PV development. The results allow us to prepare strategies for solar PV development in the energy system by reducing any potential threats and challenges or exploring further growth opportunities. In this analysis, we defined key barriers related to PV development based on multi-perspective to present a comprehensive approach; they contain internal risks (technological, market, institutional, and financial risks) and external risks (supply risks and context risks). All defined elements will be used as a theoretical framework for the study in Part II and Part III.

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Part II: Retrospective analysis of PV public policies and application of mappings for selected countries based on empirical data

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Part II. Retrospective analysis of PV public policies and application of mappings for selected countries based on empirical data

Introduction

In Part II, a retrospective analysis of PV public policies is conducted to define critical limits and challenges related to the PV policies mechanisms and to understand the mechanisms behind them. The methodological framework of this study is based on 'structured mapping', which helps conceptualize the PV policy mechanisms. In addition, our analysis gives a focus on different policy context and the historicity. The dynamics of policy mechanisms is analyzed. In this Part, we propose two types of mapping methodologies that help conduct the retrospective analysis; a schematic map of PV policy mechanisms (chapter 2) and the criteria of policy evaluation (detailed mappings) (chapter 3). Part II has four chapters.

The first chapter presents the global PV market trends. The goal of this chapter is to define major players in the PV sector by considering both the supply and demand sides. Germany, Japan and China are taken as *sample groups* of our analysis because they have played the most significant role in the global PV development over the last few decades. We also decided to study three other countries, the U.S., France and South Korea. They have less significance in the global PV market but interesting profiles.

In the second chapter, we conduct a retrospective analysis of PV public policies using the proposed analysis tool. We propose a schematic map to give a macro perspective for our cross-country comparative studies. The schematic map gives policymakers a global overview of PV policy mechanisms. Since countries usually have different PV policy features with different context, the use of a common method facilitates our cross-country analysis in a more systematic and organized way. The schematic map of PV policy mechanisms is constructed inspired by the concept of logic models presented in Part I. The application of the schematic map is followed with selected counties' empirical data over the last few decades. This parallel analysis over several time periods allows us to review the dynamics of PV policy mechanisms. In our analysis, we define three key PV policy targets: PV power growth, economic growth through PV industry development and reduction of PV costs.

In chapter 3, we develop the criteria of policy evaluation (detailed mappings) to take a deeper insight into the PV policy system. The detailed mapping is constructed inspired by a technological prospective method (*méthode de prospective technologique*) proposed by N. Popiolek. The detailed mappings explain the causal relationships between key variables and help evaluate policy efficiency. Three detailed mappings are developed with regard to important policy targets identified in chapter 2. A cross-country empirical analysis is then conducted using this method. Based on the findings, we finally discuss critical limits and risks that have emerged in the major countries. We define three critical issues in the PV policy system; financial risks associated with the FIT system in the context of subsidized policy system, systemic effects of PV integration on electricity system and the PV market crisis with globalization. An in-depth insight into each issue is given. The main purpose of this approach is to analyze the dynamics of PV policy mechanisms. It would help prepare strategic orientations for PV policies in the future taken critical limits and risks into account. Ideas of strategic movements for the PV development will be discussed in Part III.

Chapter 1. Overview of global PV market and main players (selecting the sample)

In this chapter, we aim to identify key players in the global PV sector, including both the supply and demand sides. To do so, the overall context of PV historic evolution taking both the supply (industry) and demand (installations) sides into account are briefly reviewed. The defined players will be taken as ***sample groups*** for the retrospective analysis in the following chapter.

1 Historical change with regard to PV global installations (demand)

1.1 Regional contribution

The global PV supply has demonstrated a rapid market growth with respect to the world's cumulative installed capacity, rising from 1.2 GW in 2000 to 140 GW in 2013 (EPIA, 2014).

In the early 2000's, Japan was the PV market leader accounting for over 50% of world's cumulative installations in 2002 and more than 40% of global annual growth came from Japanese market. However, since the mid-2000's, Europe took the leading position in the global PV market, with Germany in pole position; it accounted for around 70% of the world's newly installed capacity in 2005. In addition, there were installation peaks in Spain (2008) and Italy (2010). In 2013, Europe represented almost 60% of the global cumulative PV capacity with 81 GW.

However, Europe is losing its share in the global market; the shrinking demand in Europe is largely counterbalanced by the rapid rise of PV market in other regions. The paradigm change has started since 2013; new growth was implemented in non-European countries (China, Japan, US). More than 60 % of new installation in 2013 came from China, Japan and the USA.

Asian countries, with China and Japan as the central figure, currently develop the PV market faster than the European market. China and Japan rapidly increased their contributions to the global PV sector, surpassing German growth in 2013 (EPIA, Op. cit.). China became the largest PV installer in the world's PV market in 2013 with 12 GW of annual installation, while Japan installed 7 GW in 2013. The total sum of European contribution in terms of annual PV installation in 2013 is 10.9 GW; this is less than the Chinese installation. However, Germany stills remains as the largest installer in Europe with 3.3 GW in 2013.

The USA installed 4.8 GW and their cumulative capacity represents almost 10% of the global cumulative installations with 13.7 GW in 2013. In addition, other regions like Africa, the Middle East, South East Asia and Latin America started the PV market development. In particular, PV has great potential in South America and Africa, where a significant electricity demand is expected in the coming years (EPIA, Op. cit.).

Figure 38 shows leading countries in terms of cumulative installed PV capacity.

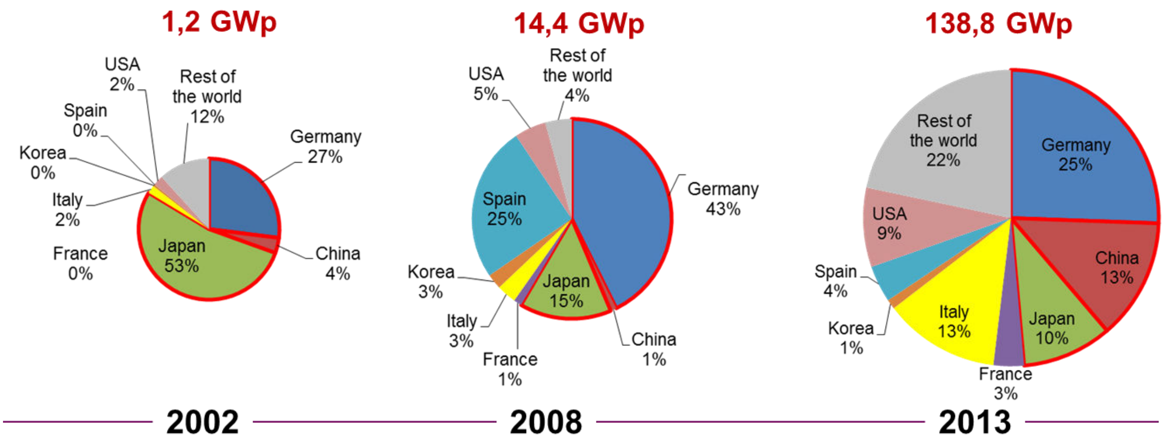


Figure 38: Demand-side: cumulative installed PV capacity in the world

1.2 Demand change in PV system type

Apart from the paradigm change of regional growth, there is a visible demand change in terms of PV system type. Off-grid systems accounted for around 10% of PV system installations in the early 2000's but the share came down to less than 1% in the current global PV market (IEA PVPS, 2014). Off-grid systems are developed in many developing countries (e.g. India, South East Asia) and isolated islands because they provide a mobile power supply solution to area where there is no traditional grid's coverage. However, these days, some countries like Australia, China and Japan put more effort to develop off-grid PV systems than in the past, supported by targeted policies; they are mainly used for rural electrification or industrial purpose. In the European countries, off-grid systems still serve for remote sites or communication devices with negligible visibilities.

The development of grid-connected systems can be seen with regard to the balance between centralized and decentralized PV systems. In the early of 2000's, most grid-connected PV systems were decentralized. However, grid-connected centralized systems became more important for the current PV systems, accounting for more than 60 % of grid-connected system installations in 2013 (IEA PVPS, Op. cit.). This change is mainly driven by China and the USA; the grid-connected centralized PV systems represent around 60% of the on-grid systems in Asian Pacific and American regions in 2013, while EU only has 30% for that.

2 Historical change with regard to PV global production (supply)

As seen, the PV industry mainly concerns the production of PV materials (feedstock, ingots and wafers), PV cells and modules and BOS components.

2.1 Polysilicon, ingots and wafers

As seen, wafer-based crystalline silicon is dominant technology in the global PV market. The manufacturing capacity of solar cells and modules are sensitive to price change in polysilicon. For example, the spot price of the polysilicon was around 70-80 $/kg at the beginning of 2011; this led to a decline in global production of modules (IEA PVPS, 2013; Osborne, 2013).

Major Polysilicon producing countries are China, Germany, Korea, the USA, and Japan. In addition, Canada, Norway and Malaysia also developed their business activities in this sector. In 2013, 230,000 tonnes of polysilicon were globally produced; four top producers, which are Wacker Chemie (Germany), GCL-Poly Energy [55] (China), OCI (Korea) and Hemlock Semiconductor (USA), represented more than 50% of the global polysilicon supply (IEA PVPS).

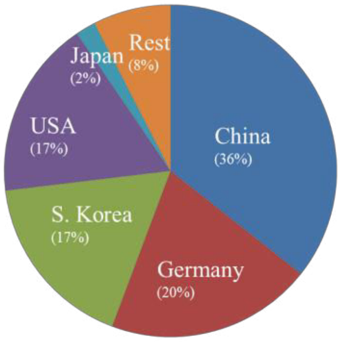


Figure 39: Polysilicon production in 2013 (IEA PVPS)

Figure 39 indicates the country participation in 2013 production of polysilicon. China is the world's largest producer and consumer of polysilicon in the current PV market. The country had 160 000t/year of production capacity and 36% of the world's polysilicon was produced in China in 2013 (82,000t). However, at the same time, China is a major importing country of polysilicon to meet the increased domestic demand; almost 50% of Chinese consumed polysilicon was imported in 2013. Germany produced 46,130 t/year of polysilicon in 2013 with Wacket Chemie's leading position. Both South Korea[56] and the USA[57] had the production capacity of 70,000 t/ year each in 2013 and produced around 40,000 t/ year each. In Japan[58], about 4 500 tonnes of polysilicon were produced in 2013.

The same manufacturers generally produce ingot and wafers together. In addition, major manufacturers[59] make silicon ingots and wafers for their own use. Accordingly, it is difficult to monitor the entire production of ingots and wafers. The leading countries in polysilicon production also take the lead in producing wafers; they are China, South Korea, Japan, Germany, Malaysia, and Taiwan.

In the recent years, China became the world's largest producer of wafers for solar cells with 40 GW/ year of wafer production capacity in 2013(IEA PVPS). Chinese solar wafer production reached around 30 GW in 2013, imported 7GW included. China-based GCL-poly Energy is the world's largest wafer maker with 10 GW/year of production capacity in 2013. In addition, Chinese makers and Japanese producers started to expand their production lines in Malaysia.

[55] GCL-Poly Energy produced 65000 t/year in 2013. Daqo New Energy, TBEA and ReneSolar Silicon are major producers of polysilicon in China.
[56] OCI, the largest Korean producer had 42 000 t/year of production capacity. Hanwha Chemical constructed a polysilicon plant with an annual production scale of 10 000 t/year and started production in 2013.
[57] Hemlock Semiconductor Corporation, REC Silicon and SunEdison and major manufactures.
[58] Tokuyama started production in its new polysilicon plant located in Malaysia with a production capacity of 6 200 t/year (this will be expanded upto 20 000t/year).
[59] For example, Yingli Green Energy (China), ReneSola (China), Trina Solar (China), SolarWorld (Germany), Panasonic (Japan), Kyocera (Japan), etc.

However, wafer-making has the lowest profit margin in the entire production value chain of crystalline silicon PV modules; the price was around 0.8 $/ piece in 2013 (IEA PVPS, 2014). In this sense, the large-scale producers are price competitive and the market is restructured around them.

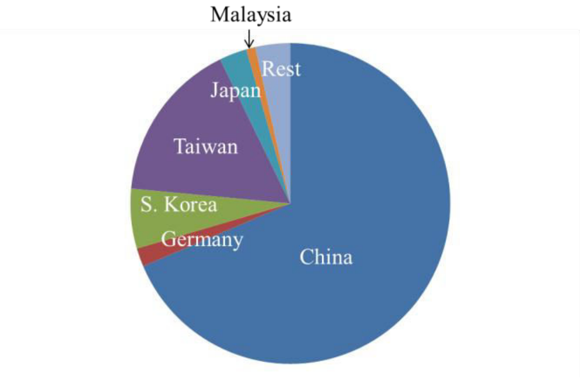


Figure 40: Wafer production in 2013 (IEA PVPS)

2.2 PV cells and modules

Since the early of 2000's, Japan and Germany have played an important role in PV manufacturing. However the involvement of the US has decreased. China entered in the PV market quite late since the mid of 2000's. The Chinese share has rapidly increased, occupying almost 60% of the world's total production in 2012 (IEA PVPS, 2002 to 2013). China became the world's largest PV cells and modules manufacturing country; it had the largest solar cell producers in 2013 like Yingli Green Energy (2,3 GW), Trina Solar (2,1 GW), JA Solar (2 GW) and Jinko Solar (1,7 GW) (IEA PVPS). Other major producing countries are Japan, Germany, South Korea, the USA, Taiwan, and Malaysia.

In recent years, Germany and the USA have reduced the solar cell production, while China, Japan, Taiwan and Malaysia have increased their production (IEA PVPS). The base for solar cell manufacturing has shifted to Asian countries with China as the center. The productions of solar cell and module generally have a similar aspect in terms of production volume and major producing countries.

The global market of solar cell and module is mainly led by wafer-based silicon production. The production of thin film module only accounts for a small portion of global solar cell markets since thin-film PV is less cost competitive compared to crystalline silicon PV products.

Around 4 GW of thin film modules (CdTe, CIGS) were produced in 2013 (IEA PVPS). Malaysia, Japan, China, Germany, Italy, and the USA, are the major producing countries of thin film technologies. The world's largest thin film PV maker is First Solar, which is based in the US. It produced around 1.6 GW of CdTe PV modules in 2013 via its production lines in the USA and Malaysia. In Japan, around 1 GW of thin-film PV modules were produced in 2013 led by Sharp, Kaneka and Solar Frontier.

The current solar cell and module industry is suffering by the overproduction issues and low modules prices. The enhanced price competitiveness is necessary to be survived in the fierce price competition; the restructuring in the global PV market is proceeding.

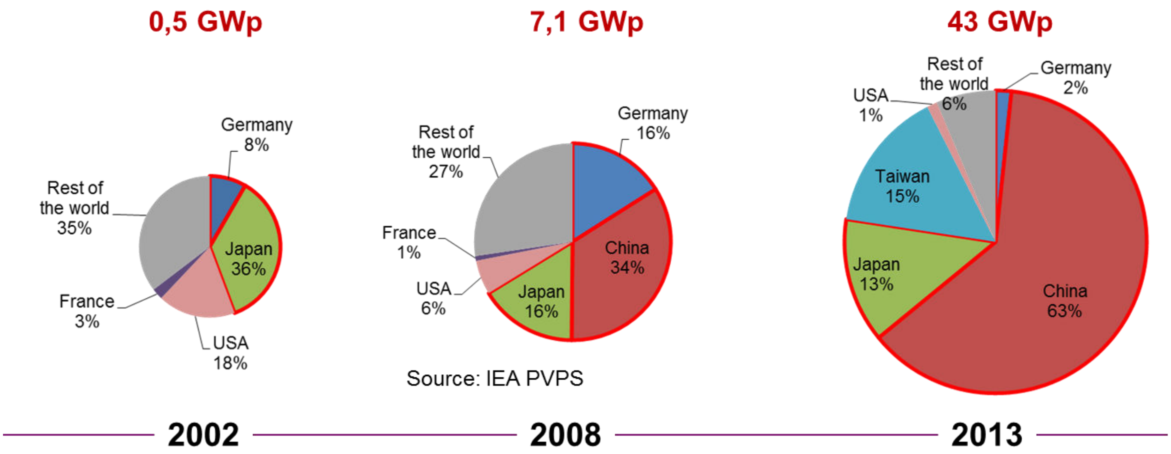


Figure 41: Supply-side: PV cells production in the world (IEA PVPS, 2002 to 2014)

2.3 Balance of system manufacturing

Balance of system (BOS) is also important in the PV system value chain because it raises the PV system costs. PV inverters are produced in many countries: China, Japan, Germany, the USA, South Korea, Australia, Canada, Austria, Italy, and Spain, etc. Local manufacturers usually dominate PV inverter production since inverter making and its installation should refer to the domestic grid codes and regulations. In addition, other components like tracking systems, connectors, DC-AC switchgear and monitoring systems suggest important business segment for several large electric equipment makers.

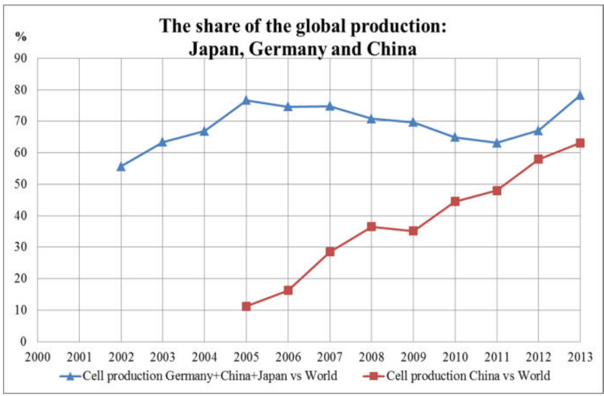
In Europe, inverters with battery storage began to be commercialized in support of PV self-consumption system. In Japan, residential PV systems are sold with battery storage supported by the national subsidy (IEA PVPS). The US-based Tesla also suggested residential battery (Tesla Powerwall).

3 Definition of key players in global PV supply-demand mechanisms

In the previous sections, we have seen the major countries in terms of PV supply and demand. Taken historic change in the global PV market into account, three countries are noticed; **Japan, Germany and China**. Japan and Germany have been driving the PV market growth focusing on both supply-side and demand-side policies over the last few decades. In addition, China is rising as a leading country in the global PV market.

These three countries occupy a considerable portion of the global photovoltaic market. Around 60% of the annual growth has resulted from these countries, excepting the installation peak periods in Spain (2008) and Italy (2010). In addition, German and Japan represent the majority of the global installations; 60% of the annual contribution in 2007 resulted from these two countries (IEA PVPS, 2002 to 2013). Chinese installations have begun to expand, supported by a national strategy to increase the PV power supply in China.

As **Figure 42** indicates, Germany, Japan, and China have been playing an important role in the global supply-side; they occupy around 70% of the global production (2012). China started to enter the market relatively late but its share has rapidly increased, occupying almost 60% of the world's total production in 2012 (IEA PVPS, Op. cit).



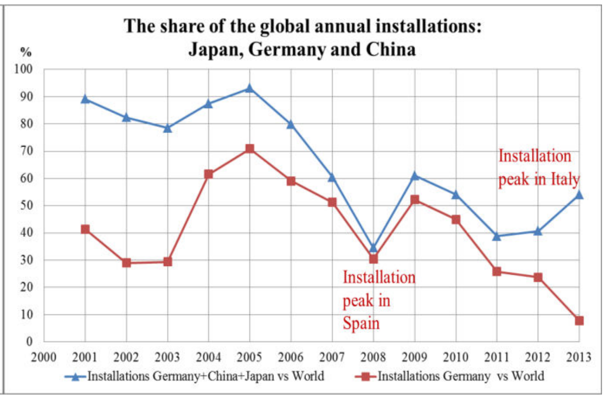


Figure 42 : Occupancy of Germany, Japan, and China in the global production (IEA PVPS, 2002 to 2013; IEA PVPS, 2013b) (%) (Left)
Figure 43 : Occupancy of Germany, Japan, and China in the global installations (IEA PVPS, 2002 to 2013) (%) (Right)

4 Conclusions

A quick overview of the global PV market evolution allowed us to define the major key players in the sector. Germany, Japan and China are taken as major sample groups for our retrospective analysis. We also decided to study three other countries that have less significance in the global PV market but have interesting profiles; U.S., France and South Korea.

Chapter 2. Schematic mapping of PV policy mechanisms (systemic vision) and applications for selected countries based on empirical data

In this chapter, we conduct a retrospective analysis of PV policy mechanisms. For that, in section 1, we propose **a macroscopic schematic mapping of PV policy mechanisms** based on the concept of logic models (see Part I) to provide a systemic view of PV policy systems in a single diagram. This schematic map suggests a general overview of the PV policy mechanisms from policy objective, policy inputs to results (outputs and outcomes) and impacts. It visualizes how policy inputs and resources driven by policy objectives turn to specific outputs with long-term impacts on society. Key contextual factors are also considered because they have an important influence on the PV policy system. It can help anticipate possible risks. In addition, some key measurable variables are extracted from the model in order to compare different countries' PV policy systems.

Then, a **retrospective analysis** is conducted to examine major countries' policies and results (outputs and outcomes) under different policy context using the developed schematic map of PV policy mechanisms. As defined in the previous chapter, **Germany, Japan, and China** are principally focused because of their important occupancy in the global supply and demand system. In section 2, section 3, and section 4, historic changes in the PV policies and results (outputs and outcomes) of Germany, Japan, and China are shown respectively. Important events and the context in both the supply-side and demand-side are also presented. In addition, in section 5, section 6, and section 7, **France, the USA, and South Korea** were studied respectively. They are studied due to their specific features in the PV market & PV policies. According to the order of schematic map, policy objectives and context are first presented to provide a general overview of PV policy choice. Next, policy inputs and results (outputs and outcomes) are discussed using identified variables in the previous section. At the end, we conclude the each case study with brief closing remarks based on a holistic perspective.

Different aspects and changes related to the PV industry and market demand over the last few decades are observed in all those countries. Each country's solar PV development is described based on the schematic map to highlight the different policy strategies and consequences. The parallel analysis over several time periods allows us to review the dynamics of PV policy mechanisms. Therefore, through this chapter, it is interesting to see how differently each country has developed the PV sector under different policy strategy and context.

1 Policy evaluation schematic mapping of PV policy mechanisms

1.1 The concept of logic model

Logic models[60] provide a visualized depiction of a program to explain key components of that very program; they are useful for demonstrating logical relations between such important elements and results within a specific context (Conrad, et al., 1999) (see Part I chapter 1). Logic models (also called the theory of change) provide a useful way to organize implicit information in mind and to display

[60] According to logic models, a program can be depicted as a logical flow chart to indicate an intended transformation of specific inputs (resources) into center activities (process) to generate desired outcomes (results) within a specific context.

how an individual or group believes how their ideas should work. Such models employ a visual description of the sequence of planned actions and their expected results and changes in a single diagram (Knowlton & Phillips, 2013). They also provide a useful way to check if intended goals are met using a mutually agreed communication. The method is practical for describing logical relations of a program among resource inputs, activities, outputs and outcomes in association with certain situations (McLaughlin & Jordan, 1999; McCawley, 2001).

Logic models offer an illustrative description of elements belonging to a specific program or organization's change initiative (the theory of change) that outlines the relationship between the elements and desired outcomes (Conrad, et al., 1999; Frechtling, 2007). Graphical depictions are useful for demonstrating a systematic logical flow of intended transformations of resources, activities, outputs, and outcomes under certain situations (Wholey, et al., 2010; McCawley, 2001).

The basic components of logic models are:

1) **Resources** (human and financial resources, also referred to as inputs),
2) **Activities** (process, program, tools, events and actions) to bring about the desired results and changes,
3) **Outputs** (directed products, goods and services provided),
4) **Outcomes** (specific changes in behavior, skills, knowledge, and status or benefits from programs),
5) **Impacts** (fundamental, intended or unintended changes in organizations, communities, or systems) (Vedung, 2008; The W.K. Kellogg Foundation, 2004).

In addition, the model includes **key contextual factors** that have an important influence on the program; however, they are not under control.

Logic models have been used to assess policy programs over the past few decades to provide a strategic tool for critical thinking. Various refinements and changes of logic models have been made to the basic concept and many organizations now use these modified methods to address their needs (Wholey, et al., 2010). Logic models provide an efficient manner to illustrate the performance history or effectiveness of a specific program or organization's change initiative over time.

1.2 Schematic mapping of solar PV policy mechanisms (holistic mapping for policymakers)

The concept of logic models is suitable for developing the schematic map to help visualize any key variables of PV policy systems in a single diagram. It also helps visualize how policy inputs and resources turn to specific outputs with long-term impacts. By doing so, it allows stakeholders to share a common basis to communicate PV policies and the consequences.

A simplified schematic map of solar PV policy mechanisms was developed in this study to understand the policy mechanisms at a glance based on the concept of logic models and the theory of change while variables are identified based on a literature review (Ribeiro, et al., 2013).

The objective is to:

- Develop common understanding among stakeholders
- Identify important variables to measure the performance of PV policies
- Facilitate the cross-country comparison of solar PV policy based on a macro-perspective

The suggested schematic map has been developed taking into account existing practices of logic models and the theory of change, such as:

- Theoretical background of a national R&D program evaluation
- Evaluating EU activities: a practical guide for the Commission services (European Commission, 2004)
- DG MARKT Guide to Evaluating Legislation (European Commission, 2008)
- Historical Case Studies of Energy Technology Innovation (Wilson, 2012).

The basic elements have been modified to adjust to the PV policy mechanisms.

The simplified logic mapping for PV policy mechanisms, which considers multi-perspectives, is shown in **Figure 44**. This model explains the logical flows of PV policies and the consequences based on a global point of view. As shown in the diagram, solar PV policy inputs are taken according to governmental policy decisions (policy objectives). Resources will be allocated as decided by the government. The direct results will be determined as outputs; these will be calculated using measurable variables such as patents, changes in manufacturing production capacities, and increases in installation capacities. Moreover, this logic framework presents outcomes (impacts) which can be sorted into direct/indirect and short term/long term. A feedback loop is important to define the mechanism dynamics. Those elements are discussed in further detail below.

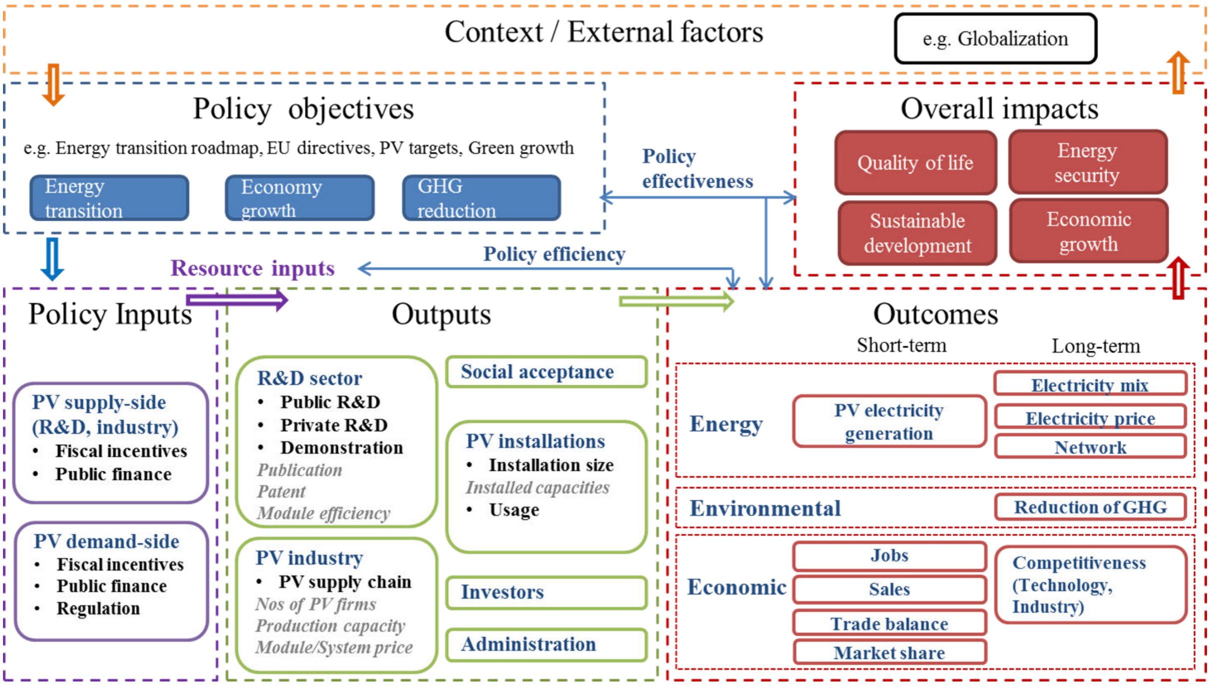


Figure 44: Schematic map of solar PV policy mechanisms (author's proposal)

1) Policy objectives

The policy objectives in PV policy mechanisms differ from one region to another according to the national development and energy policy, the regional or national contexts, and the historicity of public policies. The decision maker's political opinion of the PV energy source also has significant weight when setting those policy objectives. How the PV energy system is supported depends on how a country perceives renewable energy sources in the energy mix. As seen in the previous chapter, the general goal of policy in support of renewable energy sources is to achieve a sustainable energy system, which provides environmental, social and economic benefits to the society. This not only involves improving the cost-competitiveness of renewable technologies and sustainability in domestic energy production, but also the economic benefits such as its market share growth and job creation (IRENA, 2012b). Governments set policies to support renewable energies in order to address various objectives. To recall it, the general objectives are to (Macintosh & Wilkinson, 2011; IPCC, 2011b; Byrne & Kurdgelashvili, 2011) (see Part I chapter 3.4);

- Enhance energy security via the diversification of energy supply technologies
- Mitigate global climate by the energy transition: reduction of greenhouse gas (GHG) emissions
- Improve access to energy, particularly in rural areas (energy equity)
- Seek social development and economic benefits, e.g. job creation and economic growth.

Differences in policy focus exist among countries; while energy security and environmental concerns are the main drivers in developed countries, socio-economic development and energy access tend to be the most important aspects in developing countries (IPCC, 2007; IPCC, 2011b). In the early 1990s, only a few countries had rolled out policies to promote renewable energies. Since the early and mid-2000s, policy targets in renewable energies based on various policies have emerged in many countries (IPCC, 2011a) to address concerns of sustainable energy systems and the environment, e.g. the EU's climate and energy objectives of 3x20 for 2020, which reflect its strong will to ensure its commitment to a low-carbon and energy-efficient society.

By rolling out policy support with top-down policy objectives, the government plays a crucial role in advancing renewable energy technologies and in deploying them. In the schematic model application, the policy objectives of each country are defined in the schematic model application so as to provide the 'big picture' of the PV development pathway.

2) Policy inputs

According to the policy objectives, policy inputs are decided together with the allocation of resources. Solar PV policy inputs can be classified into supply-side (support to R&D and production) and demand-side (incentives for diffusion of solar PV energy such as subsidies to electricity production or installations) aspects (Finon, 2008).

As seen, the government support policies can be categorized into three groups; **fiscal incentives, public financing, and regulations**[61] (see Part I chapter 1) (IPCC, 2011b, p. 197) (IRENA Op. cit.).

The schematic map in **Figure 44** shows that the policy instruments supporting electricity generation via photovoltaic are reorganized into supply-side (R&D, industry development) and demand-side (installations) (Alloisio, 2011; Finon, 2008). Both policies influence the development of the PV manufacturing industry; the former directly aims at developing the PV manufacturing industry (technology-push) while the latter indirectly stimulates it to expand (demand-pull) (Alloisio Op. cit.).

Through the mix of policy instruments, government programs aim at achieving above-policy objectives. The clarification of policy input is useful for reviewing the focus area of country PV policy strategies. In the following sections, using the schematic map, policy strategies and inputs are reviewed according to **R&D, industry and installations aspects** with generated results.

3) Outputs

Outputs are generated results such as products or services in terms of technology development, economic results (industry), energy transition (installations) and other important results (administrations, social acceptance, usages and investor choices). The direct results are determined as outputs using measurable variables. Some detailed examples are given below:

- **Supply-side**
  - R&D sector (Watanabe, et al., 2000): Publications, patents (Popp, et al., 2011; Wilson, 2012), price reductions and module efficiency (Avril, et al., 2012)
  - Industry: Numbers of firms, production capacity, reduction of modules or system prices (IEA, 2010)
- **Demand-side**
  - PV installations: installation capacity, installation price reductions (Gabriel, 2014; EPIA, 2013)
  - Social acceptance (Lauber & Mez, 2004), training capacity (Malbranche, 2011), investors, administration process (European Commission, 2013)

4) Outcomes

Outcomes concern direct or indirect results and impacts in the short-term and long-term perspective; technological, economic and energy aspects. To give an example, reduced GHGs can be used to measure the environment benefits, while job creation and trade balance can be considered to review economic benefits. In addition, the energy transition's impact is determined by comparing changes within the PV electricity generation in the electricity mix (Macintosh & Wilkinson, 2011). Energy equity is a longer-term impact indicator related to energy access or electricity prices. It is also important to include network improvements to address the issues of intermittency. The

[61] **Fiscal incentives**: reduction of players' contribution to the public treasury through tax deductions (such as income tax or other taxes), rebates, grants, **Public financing**: public supports such as loans, equity or financial reliability such as guarantee, and **Regulations**: rules to guide or control.

competitiveness of the industry can be determined by reviewing changes in the global market share. In this study, the following measurable variables are considered in order to review PV policy results.

- **Energy transition: PV electricity generated and percentage in the energy mix**
- **Environment benefits: GHG emissions avoided**
- **Economic benefits: jobs, trade balance, sales, and market share**

Outcomes combined with outputs will be presented as results in the country analysis.

5) **Overall impact**

These defined outcomes ultimately aim at improving the overall effects on society relative to the **quality of life, energy security, sustainable development** (IPCC, 2007; IPCC, 2011b) **and economic growth** (Solangi, et al., 2011) through the development of solar PV energy systems. In the comparative analysis, the overall impact associated with the country's policy objectives is reviewed to clarify differences in the social benefits generated in each country.

6) **Key contextual factors**

Key contextual factors are important in the mechanisms. This includes various contexts, environments, natural and human resources, and external factors that influence the PV policy mechanisms. They are not, however, under control. The influencing factors hold different aspects in regional, national and energy contexts. There are various factors affecting the mechanisms, e.g. energy price changes, human resources such as the price of labor (Grau, et al., 2012) or education, electricity network quality (IEA PVPS), electricity mix, scarcity of domestic energy supply (Alloisio, 2011), manufacturing capabilities of fossil fuels (Alloisio, Op. cit.), the social opinion on energy sources (Lauber & Mez, 2004), financial situation, etc. The key contextual factors change over time and are influenced by various aspects.

7) **Evaluations**

It is important to define the desired results in comparison with policy objectives for the entire evaluation process. As seen in the previous chapter, there are some criteria to assess energy policies that can be found in most literature; they are effectiveness, efficiency, equity, institutional feasibility (IPCC, 2011a), replicability (IRENA, 2012b), consistency and coherence (IPCC, 2011b; Bohm & Russel, 1985). Among them, effectiveness and efficiency are the most commonly used standards to determine the success of policy instruments (IPCC, 2011a); **effectiveness**: to what extent is the intended objective met? (policy objectives vs. outcomes), **efficiency**: what is the ratio of outcomes to inputs? (policy inputs vs. outcomes). This study attempts to review the effectiveness of PV policies so as to assess which desired results are obtained compared with the policy objectives (see Part I chapter 1.4).

This schematic map attempts to provide an overview of a country's PV policy roadmap from policy choice under certain policy contexts to the desired results and overall impact at the specific end. Accordingly, the map is used to explain the different pathways of PV development strategies and results in each country, rather than focusing on clarifying one-to-one linear relations among elements (this will be discussed in chapter 3).

The retrospective analysis using the common systematic tool facilitates comparative analysis by highlighting differences in policy strategies and consequences relative to the different PV development pathways. This approach clarifies the success and failure factors, and in doing so, comparative case studies can improve future policy actions to reduce risks or to respond to unexpected results. More importantly, it helps policymakers to conduct regular policy assessments or to prepare new strategies and actions when facing unexpected results or context changes. In the following sections, a retrospective analysis of public policies in favor of solar PV development to date is conducted using the schematic mechanisms model.

2 Historic changes in PV policies of Germany

2.1 PV policy history: policy objectives and context

Germany has played a significant role in the development of the global solar PV market, being one of the pioneering countries over the past few decades.

Germany began to promote the use of renewable energies as early as the 1970s when faced with oil crisis (Jacobsson & Lauber, 2006). Solar PV energy was one of the sustainable substitutes that could increase the national energy security. Later, the Chernobyl nuclear accident provoked social pressure to shift towards more sustainable energy sources. This has been later enhanced with the government's decision on nuclear phase-out by 2022. In addition, the EU's GHG emission reduction targets drove Germany to engage in more sustainable energy systems. German Energiewende (energy transition) aims to produce 80% of the electricity from renewable power such as PV and wind by 2050[62].

Accordingly, the German PV policy objectives aimed at developing a sustainable substitute of conventional energy sources and at mitigating the global climate change (Lauber & Mez, 2004).

The Renewable Energy Sources Act (EEG), which was published in 2000, supports these national energy transition goals (Fischer, 2011). Under the EEG, the German government decided to stimulate the increase in demand by including PV energy systems. Germany also intends to boost the PV industry to generate more economic benefits (e.g. economic growth, job creation) (Alloisio, 2011). Like this, the country has a well-balanced development path focusing on both supply (R&D, industry) and the use of solar PV systems (installations).

2.2 Policy inputs and results: supply and demand

2.2.1 R&D: policy inputs and results (outputs and outcomes)

In the solar PV development process, Germany almost followed the classic linear model of innovation from focusing on early R&D investment and then expanding to demonstration and commercialization (Lauber & Mez, 2004; Mints, 2012). Since the early 1980s, German R&D on solar PV and its demonstration were developed through the combined involvement of research centers, universities, and PV industry. This has created a close network in the PV sector.

[62] Renewable targets in Germany: 40-45% by 2025, 55-60% by 2035, and 80% by 2050.

Since Germany's disengagement from nuclear power in the early 2000s, part of the nuclear R&D budget was transferred to the renewable energy sectors (Lauber, Op. cit.). With the inflow of cheap Chinese products since the late 2000s, German R&D started to focus on further reducing the production costs of silicon-based technologies to support the German industry. At the same time, the country strengthened its skills in PV components and equipment (Grau, et al., 2012).

The continuous **R&D expenditures** in PV demonstrated the German government's supportive position towards PV technology development.

US$M	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Germany	22.2	33.6	3.3	51.9	82.5	61	87.4	73.5	84	77.8	66	250

Table XXV: Public budgets of PV R&D in Germany (IEA PVPS, 2002 to 2014)

The German steady effort has resulted in an increased cell performance and reduced production costs per unit (this will be further discussed in the following part of PV industry). The silicon module efficiency improved to over 20% in 2012 thanks to continuous R&D (Siemer & Knoll, 2013). The domestic R&D results can be reviewed with changes in **patents**. Germany was responsible for a significant proportion of the global patents. However, its contribution in silicon refining became less important in recent years because of the increased market influence of new entrants (e.g. China, South Korea). The new entrants induced overproduction and caused a drop in prices (IEA PVPS, 2013; 2014). Moreover, Germany might have been suffered from a disadvantageous exchange rate for Euro (EUR) to US dollar (USD). In addition, German firms faced the increased electricity tariffs and this penalized the competitiveness of German power-intensive industry like silicon production. The German firms started to focus on overseas production (Wacker).

Patents cell & modules	1995	2000	2004	2007	2010	2013	Patents silicon refining	1995	2000	2004	2007	2010	2013
Germany (%)	6.4	7.3	7.7	7.8	7.7	6.3	Germany (%)	17.0	13.9	13.4	11.2	8.4	7.0

Table XXVI: Patents for cells & modules and patents for silicon refining (Unit: cumulative % of the global patents) (Espacenet)

	1980s	1990s	2000-2004	2005-2009	2010-2011
Germany (%)	6%	20.6%	15%	13.7%	11.1%

Table XXVII: German patents application filed under the PCT (OECD.Stat)

2.2.2 PV industry: policy inputs and results (outputs and outcomes)

Germany began to invest in the PV industry not only to meet its environmental goal (GHG emission reduction) but also to obtain **economic benefits** (employment and profits) (Alloisio, 2011). A great deal of funding was provided, mainly from the German federal government, EU, and the German federate states (Länder) in order to support the government's incentive (IEA PVPS Germany, 2002 to 2014; Grau, et al., 2012). There were also various industry support instruments; grants or cash incentives for direct investment, reduced-interest loans by the German development bank (national), and state development banks and public guarantee to secure bank loans (Grau, et al, Op. cit.). The German PV market developed thanks to synergies resulting from the success of technology-push and market-pull policies (Alloisio, Op. cit.).

In this section, the results of the PV industry are reviewed with respect to changes in the **manufacturing capacity** and the **module production cost**. Economic benefits are seen via **jobs, sales** and **trade.** In addition, the competitiveness of the PV industry is considered together with the **market share.**

German PV system costs have decreased rapidly since the 1980s, ever since the commercial applications stage started (Bhandari & Stadler, 2009). Focusing on both R&D and industry sectors, Germany continues to put its efforts on reducing the production **costs of solar cells and PV modules**; the **module price** reduced from $6.8/Wp 1992 to $2.9/Wp in 2008, which further reduced to $0.69/Wp in 2012 with the emergence of Chinese products boosted by large-scale production. **Figure 45** shows the German industry's continuous evolution in the **global solar cell production** from 2000 to 2013. The German cell **manufacturing capacity** increased 51 times from 57 MW in 2000 to a peak of 2,919 MW in 2011, before it was halved in 2012 due to the PV crisis. The **system price** also decreased from $8/Wp in 2000 to less than $3/Wp in 2012 for rooftop systems under 10 kW (IEA PVPS, 2002 to 2014).

Furthermore, the German PV industry created economic benefits; 128 thousand direct **jobs**[63] in 2011 with **sales** valued at US$ 21 billion and **exports** to US$ 7.3 billion in 2011 (IEA PVPS, Op. cit.) (UNCOMTRADE).

There is one thing that needs to be mentioned; even though Germany successfully accomplished the industrialization of PV over the last decades, the domestic production capacity did not fulfill the country's domestic demand for installations, and Germany imported PV products to some extent (BMU 2009).

However, the German industry has higher production costs than its international competitors, which explains why it was penalized and finally collapsed in 2012 and 2013 (IEA PVPS, 2011; 2013; European Monitoring Center on Change (EMCC), 2014). Its production reduced sharply from 2012 because of the downsizing of its PV industry (IEA PVPS, 2013); it was impacted by fierce competition from Chinese producers since 2008 and by the global economic crisis. Germany's industry **market share**[64] in PV cell production reduced in the global PV market from 22% in 2007 to 2% in 2013.

In addition, faced with the European PV crisis and fierce global competition, the German PV industry fell hard; 68,000 **jobs** were lost between 2011 and 2013 and **export** decreased by 53% (IEA PVPS, Op. cit.) (UNCOMTRADE). In addition, many German PV firms went to the bankruptcy (industry crisis), and this phenomenon started to threaten the German economy.

Furthermore, faced with the price competition with Chinese manufactures, the German PV sector underwent a transformation; the German industry strategically decided to focus more on highly skilled sectors such as refining silicon and equipment production (Grau, Op. cit.) to offset the market share drop of solar modules in the global market.

[63] Incl. jobs related to PV manufacturing and PV installations.
[64] Author's calculation based on IEA PVPS data.

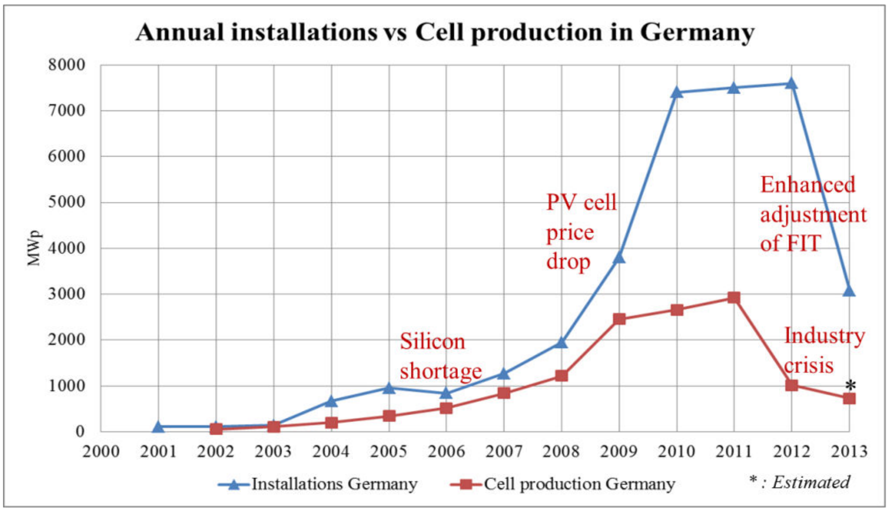


Figure 45: Annual installations vs. cell production in Germany

	Silicon (t)	Ingot/Wafers (MW)	Cells (MW)	Modules (MW)
2004	2800	120	198	198
2007	8000	415	842	875
2010	30100	1990	2700	2460
2013	46130	800	1230	1412.5

Table XXVIII: PV production in Germany

2003	2007	2008	2010	2011	2012	2013
10,000	42,300	48,000	133,000	128,000	100,000	60,000

Table XXIX: Solar PV jobs in Germany (2003 (IEA PVPS Germany, 2003); 2008-2013 (IEA PVPS, 2002 to 2014))

	2004	2007	2010	2013
Domestic sales (US$M)		7816	28936	7932
Exportations (US$M)	946	3522	8098	3490
Importations (US$M)	1879	4865	16026	3546

Table XXX: Economic results from PV industry in Germany (UNCOMTRADE)

2.2.3 Installations: policy inputs and results (outputs and outcomes)

A policy that supports demand helps to promote national PV installations by inciting commitments from more stakeholders. German has a long history in PV installation; the first German PV targeted subsidy program started with the '1000 Solar Roofs Initiative' (1991-1995) (Grau, et al., 2012; Byrne & Kurdgelashvili, 2011). The '100,000 Solar Roofs Initiative' (1999-2003) was then rolled out, which caused a rapid increase in the installation of PV systems in the early 2000s (Lauber & Mez, 2004). The Renewable Energy Sources Act (EEG) was set up in 2000 to provide legal support for the government's energy transition towards a power supply using more renewable sources.

The main driver of German PV development was the 'Feed-in Tariffs' (FIT) scheme, which was launched in 2000 under the EEG and then amended in both 2004 and in 2009. This scheme was behind the German solar PV boom from 2004 (Grau et al., Op. cit.) (Yang, 2010). The commercialization of solar PV and its industry grew in Germany with the enhancement of the FIT in 2004 that aimed to counterbalance the end of 100,000 Solar Roofs' program (European Commission, 2012).

In order to respond to the market change with price drops, the German government then adjusted the FIT scheme. In 2009, the price of PV systems reduced much faster than expected; the German government introduced a corridor system to adjust the FIT in 2009 with the objective of reducing the uncontrolled increase of installations and any windfall effects (de La Tour, et al., 2011).

The Table XXXI shows the constant commitment from the German government and the expanded installations since 2000. Germany invested €53 billion (cumulated for the 20-year contract) in direct support for PV deployment through the FIT system until 2010 (Lütkenhorst et al. 2014). The FIT system became a financial burden, which raised a number of issues as to the efficiency of the policy. This issue will be further discussed in the following chapter (see Part II chapter 4.1).

Germany	2000	2004	2007	2010
FIT (annual) (M€)			1,447	4,472
FIT (accumulative over 20 years) (M€)	559	4,374	26,534	53,271
Cumulative PV installations (MWp)	76	1,105	4,170	17,320

Table XXXI: FIT investments on an annual basis and accumulated over 20 years, as well as cumulative installations in Germany (Lütkenhorst & Pegels, 2014; IEA PVPS, 2002 to 2013)

In this study, policy results are reviewed through direct changes in the installed capacity and the impact on the energy transition (**electricity generated using PV, PV ratio in the electricity mix**).

Thanks to the government's constant affirmation through support policies, Germany achieved a successful energy transition by turning renewable energies from a niche into a visible energy source (Gabriel, 2014). Germany has been the global market leader in PV system installations since 2005 with a cumulative installation of 35.7 GW in 2013 (IEA PVPS, 2002 to 2014), representing 26% of the global installation (IEA PVPS, 2013b). In addition, the country became the world's largest PV market (EPIA, 2014), increasing the PV contribution to the national electricity production using PV technology from 0.2 TWh (0.04% of annual electricity production) in 2002 to 33.4 TWh (5.6%) in 2013 (Eurobserv'er, 2013; Index Mundi; Fraunhofer ISE, 2012; IEA PVPS, 2014). The **business value** of the German PV installation market was valued at $17,520 million in 2012.

2.3 Conclusions of Germany case study

German PV development started with a focus placed on its energy transition towards a sustainable energy supply system; however, technology development through continuous R&D activities and industry growth are also important objectives. The well-balanced policy mix around supply and demand helps the country take the leading position giving visible results with respect to the energy transition and economic benefits until recently.

However, the situation changed as the competition started with the emergence of Chinese large-scale production capacity in the late 2000s. The German PV industry was influenced by the inflow of cheap Chinese products, thus provoking economic damage (job loss, trade deficits). The current German PV sector is experiencing a slowdown and the PV growth engine is shifting to other regions. Furthermore, systemic impacts of PV power in the electricity mix began to be observed; e.g. PV electricity overproduction raised the issue of a negative electricity gross price for the European electricity market (RTE, 2013).

3 Historic changes in PV policies of Japan

3.1 PV policy history: policy objectives and context

The enhancement of the national energy security is the top energy policy issue in Japan. Due to the lack of domestic natural resources, the Japanese economy depends heavily on imported primary energy sources (Japan's energy imports from 87% in 1980 to 94% in 2013 (The World Bank, 2014)). The oil crises in the seventies gave a huge impact on the national economy that was heavily dependent on overseas oil. The country attempted various ways from diversifying energy supply sources, increasing energy efficiency to developing new energy sources like solar. Furthermore, in the 1980s, the interest in global warming and climate change issues required Japanese government to work more on the development of new clean and sustainable energy sources.

In this context, Japan decided to develop solar PV energy in order to increase the national energy security and to mitigate climate change. The country considered the solar PV energy as a good alternative renewable energy sources to conventional fossil fuels. The government's investment in the PV sector has increased after having experienced the two oil crises in the 1970s. Japan seriously started using solar PV energy in the energy supply system from the 1980s. However, renewable energy had still accounted for a small part in Japan's total energy supply (~ 2%) (Hahn, 2014). After the Fukushima accident, Japan decided to expand the fraction of renewable energies in the energy mix (European Commission, 2012).

Similar to the German case, a mix of technology-push policies (Sunshine program) and demand-side policies (Investment subsidies) enabled Japan to develop the solar PV market over the last decades (Kimura & Suzuki, 2006). Japan gave a well-balanced focus on PV development from R&D, industry and PV installation diffusion.

3.2 Policy inputs and results: supply and demand

3.2.1 R&D: policy inputs and results (outputs and outcomes)

Japan first began solar PV R&D in the 1950s and solar cells were used for spacecraft and telecommunications in the 1960s and 1970s before they seriously started using them in the energy supply system from the 1980s. Japan soberly began to invest more in PV R&D in search of alternative renewable energy sources to conventional fossil fuels in the seventies.

The governmental Sunshine program was rolled out in 1974 to advance R&D on renewable energy technologies; solar energy was one of the major sectors in the program, supported with stable R&D budgets. Thanks to this program, in the 1980s, Japan was able to progress on a technological level; the knowledge stocks in the PV sector had increased while improving PV efficiency and reducing costs. In addition, Japan conducted many demonstrations as part of this program to reach commercialization of solar power generation, assuring the reliable supply of grid-connected PV systems. However, the market was insignificant at that time (Kimura, Op. cit.). Japan's consistent efforts to advance PV technologies stimulated the private sector's participation in the PV sector.

Japan demonstrates steady **investments in PV R&D** (see Table XXXII). The R&D effort can be seen with **patent** contribution change in the world; Japan has a visible contribution in both PV cell/module and silicon refining technologies.

US$M	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Japan	59.1	84.5	60.5	37.2	27.2	38.9	35.8	44.5	68.1	102	130	89.8

Table XXXII: Public budgets of PV R&D in Japan (IEA PVPS)

Patents cells & modules	1995	2000	2004	2007	2010	2013	Patents silicon refining	1995	2000	2004	2007	2010	2013
Japan (%)	5	7.4	8.7	9.6	10	10	Japan (%)	1.6	3.9	6.5	13.1	13.8	12.5

Table XXXIII: Patents for cells & modules and patents for silicon refining (Unit: cumulative % of the global patents) (Espacenet)

	1980s	1990s	2000-2004	2005-2009	2010-2011
Japan (%)	16.9	10.2	26	24.3	35.4

Table XXXIV: Japan patents application filed under the PCT (OECD.Stat)

3.2.2 *PV industry: policy inputs and results (outputs and outcomes)*

The government's strong message for consistent commitments to PV development through the Sunshine program stimulated the investment of private firms in PV R&D in the 1980s and established the foundation of the PV industry in Japan.

Through the constant effort to reduce production costs, Japan has reduced the price of solar cells and PV modules from US$ 8.3/Wp in 1992 to US$ 3.7/Wp in 2002, keeping almost the price level until 2012 (US$ 3.6/Wp) (IEA PVPS, 2002 to 2013). Moreover, Japan maintained a vertically integrated industry across the whole value chain from silicon purification to integrated PV systems, even though Japan recently started to reduce its silicon production (IEA PVPS Japan, 2012) due to the high cost of electricity (Barua, et al., 2012) and the global over-production (IEA PVPS, 2013). Furthermore, many **PV jobs** were created; 47,000 jobs in 2012 for solar energy sector in Japan (IEA PVPS, Op. cit.) and 101, 300 jobs in 2013 (IEA PVPS, 2014) (Table XXXV).

2003	2008	2010	2011	2012	2013
11,300	18,100	41,300	45,000	47,000	101,300

Table XXXV: Solar PV jobs in Japan (2003 (IEA PVPS Japan, 2003); 2008-2013 (IEA PVPS, 2002 to 2014))

The main difference between Japan and Germany is that the **Japanese market is more closed due to complicated institutional barriers.** Up until 2012, the Japanese market was relatively closed to foreign competitors due to its standards (e.g. minimum performance and certification requirements). It is mandatory to fulfill these requirements issued by Japan Electrical Safety & Environment Technology Laboratories (JET) in order to receive the subsidy for residential PV systems (IEA PVPS Japan, 2009 to 2012); this created technical and institutional barriers for entering the Japanese market. This policy has had, however, an adverse effect; Japanese **module and system prices** are more expensive than those in Germany and China (US$ 3.6/Wp in Japan in 2012 compared with less than US$ 1.1/Wp in Germany and US$ 0.71/Wp in China (IEA PVPS, 2002 to 2013)).

Japan was an exporting nation of PV products until 2012; Japanese production had always exceeded their domestic need since 2002 and their production surplus was exported. Between 2000 and 2007, Japanese **exports** for the German market amounted for 3 billion US$ (UNCOMTRADE). However, since 2012, Japan became an importing country. The Japanese PV industry rapidly raised its **production** (3.6 GW of module production in 2013) but it was nonetheless insufficient to meet the rise in demand, thus the importation of foreign PV products accelerated (IEA PVPS, 2013b; Japan Photovoltaic Energy Association (JPEA)). Japan imported a noticeable fraction to feed the rapidly increasing demand in installation for the first time in its PV development history in 2012-2013 (see **Figure 46**).

	Silicon (t)	Ingot/Wafers (MW)	Cells (MW)	Modules (MW)
2004	1000	327	604	590
2007	1391	670	923	422
2010	6302	669	2311	2315
2013	>1000	1200	2992	3609

Table XXXVI: PV production in Japan (IEA PVPS, 2002 to 2014))

	2004	2007	2010	2013
Domestic sales (US$M)	1849	1274	6574	13123
Exportations (US$M)	4629	5472	6446	4725
Importations (US$M)	1002	1131	2189	7007

Table XXXVII: Economic results from PV industry in Japan (UNCOMTRADE)

3.2.3 Installations: policy inputs and results (outputs and outcomes)

Japan has a long history of supporting the installation of PV systems. In the late 1990s, the Japanese government started market deployment policies for mass installations to create the market. Various policy instruments were prepared to promote grid-connected PV systems; a simplified administration process, technical standards, net-metering system, and investment subsidies for residential PV systems (Kimura & Suzuki, 2006). These policy actions were introduced not only in association with the global movement to combat climate change, but also in line with pressure to produce visible results from the long-term investment of the Sunshine program (Kimura & Suzuki, Op. cit.). In addition, the PV industry lobbying influenced this political support.

Japan	2000	2004	2007	2010	2011
Residential PV support (MUS$)	134	48	41	628	463
Cumulative installations (MWp)	330	1,132	1,919	3,618	4,914

Table XXXVIII: Subsidy amounts and installations in Japan (Unit: million US$ and MWp) (Kimura & Suzuki, 2006; IEA PVPS Japan, 2002 to 2012)

Japanese installations were developed on the basis of a subsidy program for residential PV systems, with the ‘700 Roofs’ program rolled out to provide 50% support for PV system installation investment in 1994 (Kimura & Suzuki, Op. cit.). Since the end-1990s, PV system installations in the residential sector have rapidly increased **with support of the residential PV subsidy program**, which was the main driver behind the growth of Japanese installations (see Table XXXVIII).[65] As shown in **Figure 46**, this program stimulated a small but constant growth of annual installations. The residential subsidy program reduced its support to 3% in 2005 before closing down the program with the intention to incite producers to reduce costs, leaving the same financial costs for consumers. Nonetheless, the subsidy program was restarted in 2009 to overcome the sluggish installation dynamics under the new regime (IEA PVPS Japan, 2009).

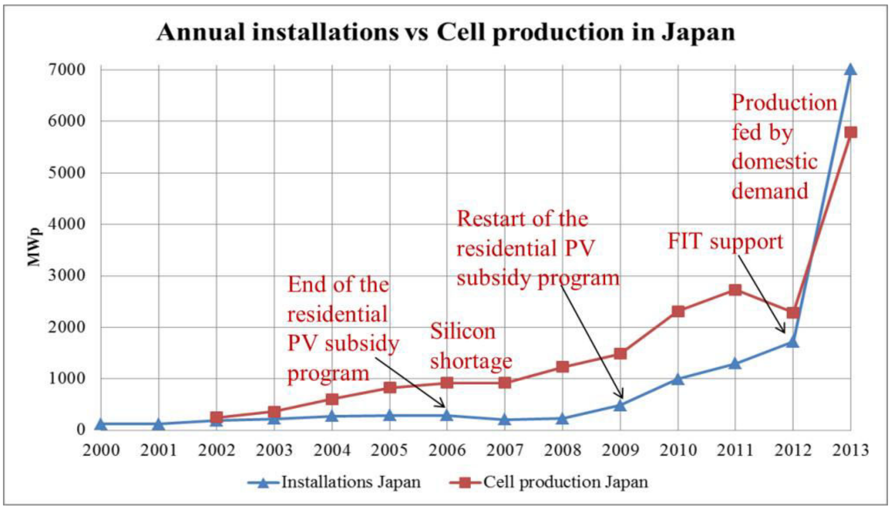


Figure 46: Annual installations vs. cell production in Japan (IEA PVPS, 2002 to 2013)

From an early stage, environment-conscious high-income groups led the Japanese PV system diffusion pathway as a niche market creation. As was the case with the FIT system, which was the main driver for the rapid increase in German PV installations, Japanese users were willing to pay more even though they were not economically profitable because they wanted to participate in the global move for combating climate change (Kimura & Suzuki, Op. cit.). The initial success of the Japanese PV system can be seen as a result of a harmonious combination of various stakeholder commitments embracing the government's consistent long-term policies, the somewhat risk-taking participation of private firms and a strong level of social acceptance.

After the Fukushima accident, Japan decided to expand the fraction of renewable energies in the energy mix (European Commission, 2012). The Japanese government launched a new policy at the beginning of 2012 to increase installations in search for growth engines outside the residential sector (IEA PVPS, 2013b) based on the FIT scheme for installations over 10kW. Due to the higher cost of the Japanese systems, the FIT was set at a high level (42 JPY/kWh[66]) (IEA PVPS Japan, 2012). The effect of the policy was already visible in 2013. Unlike the German case, Japan's installation soared after the global crisis, representing about 18% of the world's installation growth with 7 GW in 2013. It became the major installer in the global PV market (see **Figure 46**). Japan's PV development increased the fraction of PV in the national energy mix up to 1.4% in 2013, producing 14.3 TWh (IEA PVPS, 2014).

[65] The subsidy program for residential PV systems was managed by the Ministry of Economy, Trade and Industry (METI).
[66] About US$ 0.52/kWh.

3.3 Conclusions of Japan case study

The solar PV energy has been highlighted as a prospective option of alternative energies in Japan. Japan's PV development has conducted with an equal focus placed on three dimensions; R&D, industry growth and PV market diffusion. The well-balanced policy mix around supply and demand with the long-term support from the government allowed Japan to secure a constant growth of PV energy. Japan demonstrated continuous efforts to advance the PV technologies and to increase its domestic installations. Furthermore, Japan performed well in PV production and gained exportations until recently.

However, the actual participation in energy supply using the solar PV still has room to grow. However, Japan has recently started to open its market more to foreign products to feed the increase demand in PV products. In addition, the FIT started to place much financial burdens. In this regards, the German case can provide Japan with a valuable lesson for future policy strategies.

4 Historic changes in PV policies of China

4.1 PV policy history: policy objectives and context

China's energy policy mainly aims at securing a stable energy supply to balance its growing energy needs. The Chinese PV market development followed different strategies from a balanced pathway between supply-side and demand-side in Germany and Japan. China's PV development started with the supply of electricity to off-grid rural areas.

China entered relatively late into the global photovoltaic market. It was not until the mid-1980s that the industrialization of PV materials started.

Under the 10th (2001-2005) and 11th (2006-2010) 5-year plans in China, the government strove to control air pollution by SO2 and CO2 (by-products resulting from the excessive use of conventional energy sources, mainly coal).

In 2006, under the 11th 5-year plan, PV was selected as a technology to improve national knowledge on energy technologies. However, the municipal government first aimed at developing the PV industry to promote high-tech manufacturing in pursuit of economic benefits (Deutch et al. 2013) under the regional industrial policy to boost economic benefits.

Under the 12th 5-year plan (2011-2015), the solar PV industry was included in the list of national initiatives to further expand the new energy industry by developing clean energy technologies and related industries (British Chamber of Commerce in China, 2011). The government also aimed at developing the domestic market through the expansion of large-scale power plants (Lewis, 2011).

Like this, China's political priority in terms of PV development was industry-focused rather than energy transition or mitigation of climate change.

4.2 Policy inputs and results: supply and demand

4.2.1 R&D: policy inputs and results (outputs and outcomes)

China took up research work to develop solar PV in the late 1950s and entered the application stage in the 1970s. However, the Chinese government efforts in PV R&D were negligible until recently. China somewhat took advantage from the knowledge spillover from technologically advanced countries (e.g. Germany). This allowed China to jump straight in PV industry; it mainly aimed at increasing the production of cells and modules with focus on easy-to-follow technologies rather than conducting serious R&D for technology development (de La Tour, et al., 2011).

Table XXXIX indicates China's resource-allocation decisions for R&D expenditures in PV.

R&D (US$M)	2001-2005	2006-2010	2012
China	US$ 5.2-6.2 M	US$ 25.6 M	US$ 79 M

Table XXXIX: Public budgets of PV R&D in China (Campillo & Foster, 2008; IEA PVPS, 2013)

China's R&D expenditures are barely remarkable until the mid- 2000. China sharply increased its **budgets of PV R&D** in the recent years to support PV industry. China recently started to focus more on R&D to advance PV-related technologies such as silicon production to catch up with the major producing countries (de la Tour et al. 2010; IEA PVPS). Therefore, China has only recently gained visibility in terms of producing international **patents**.

Under its 12th plan, China included the PV sector in the list of government-driven R&D initiatives; e.g. Si-cell efficiency of 20% and thin film cell efficiency above 10% and reducing production costs (IEA PVPS).

Patents: cell & modules	1995	2000	2004	2007	2010	2013	Patents: silicon refining	1995	2000	2004	2007	2010	2013
China (%)	0.3	0.4	0.9	2.0	4.1	2.7	China (%)	0.8	0.6	0.4	2.5	7.1	5.4

Table XL: Patents for cells & modules and patents for silicon refining (Unit: cumulative % of the global patents) (Espacenet)

	1980s	1990s	2000-2004	2005-2009	2010-2011
China (%)	0	0	0.4	1.9	4.2

Table XLI: Chinese patents application filed under the PCT (OECD.Stat)

4.2.2 PV industry: policy inputs and results (outputs and outcomes)

In contrast with Germany and Japan, China adopted a different industry policy strategy. The nation's industrial policies were export-oriented. China first focused on easy-to-follow technologies establishing production lines of labor-intensive manufacturing (modules and cells) because of accessibility to technology and low energy prices.

China's PV industry has experienced an explosive increase since the mid-2000s, supported by government aids for innovative industry [67], particularly in crystalline silicon solar cell production (Zhang & He, 2013). The Chinese government supported PV manufacturing investment through innovation funds for small technology-based firms, regional investment support policies [68] (2009) issued by some Chinese city governments, as well as loans and easy credit provided by government or

[67] The industry support is mainly given by local governments and the data are not available. This issue will be discussed in Part III during the analysis of the interactions between China and Germany.

[68] E.g. Refunds of loan interest, of electricity consumption fees, land transfer fee, corporate income tax, and of value added tax payment.

state banks for manufacturers. In addition, China's low labor cost and low energy price facilitated the industry's expansion by reducing production costs (Grau, et al., 2012). This is further discussed in Part III chapter 2.

China is somewhat dependent on imported refined silicon and equipment for its massive production due to the technological barriers (de La Tour, et al., 2011). To give an idea, in 2013, despite its leading position in the PV manufacturing, about the half of its needs were met by imported silicon; 82,000 metric tons were produced and 80,000 metric tons were imported (IEA PVPS, 2013b).

In this regard, from 2006, China started to focus more on PV material production and its capital-intensive upstream industry (silicon purifying) through R&D to advance related-technologies which had been lagging since 2009 (IEA PVPS China, 2011; 2012; de La Tour, et al., 2011).

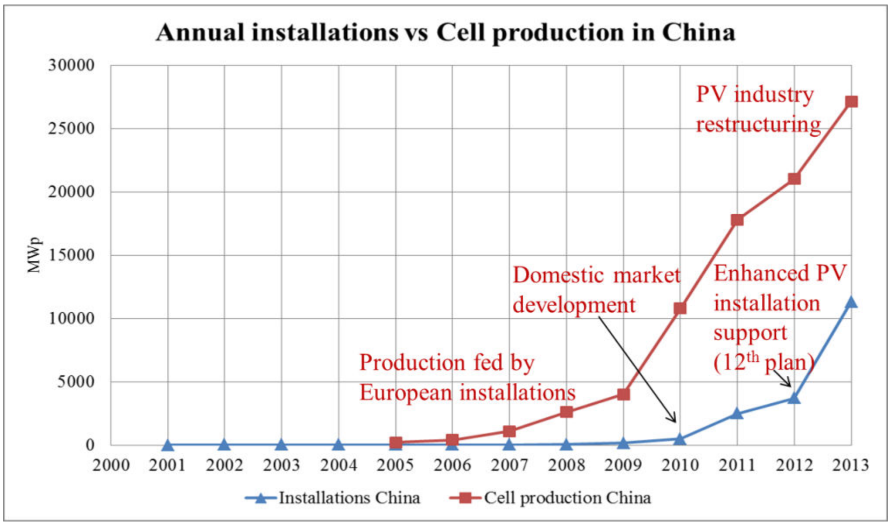


Figure 47: Annual installations vs. cell production in China (IEA PVPS, 2002 to 2013; 2013b)

China's action has yielded remarkable results, obtaining the leading position in the solar PV manufacturing industry in a very short time (Xie, et al., 2012). China increased its **production of cells** by a factor of 23 from 2007 to 2013. China became the largest manufacturer in the solar PV market in 2007, representing 29% of the global **production of solar PV cells** (IEA PVPS, 2013; 2013b). Their **module prices** have reduced in a very short time with mass production; from US$ 4.73/Wp in 2007 to US$ 0.67/Wp in 2013 (IEA PVPS, 2013b; The World Bank). Its **market share** has also grown from 16% in 2006 to more than 60% in 2013 (IEA PVPS, 2002 to 2014).

Through the industry development, China created hundreds of thousands of **jobs** (see Table XLIII) in the PV sector and **export** amounted to US$ 17.5 billion of PV materials in 2012 (UNCOMTRADE). In addition, major PV manufacturers were now headquartered in China. The PV industry accounted for a substantial fraction of the Chinese economy, representing US$ 48 billion in 2011 (0.6% of **GDP**) (IEA PVPS China, 2011). However, China's PV industry is heavily dependent on the overseas market.

Moreover, faced with strong global competition after 2009, China's easy access to credit and permissive standards gave another advantage for local manufacturers to gain scale effects for building gigawatt (GW)-scale plants (Goodrich, et al., 2011). Since mid-2000, China has exported the majority of its module production. China's expansion of production capacity was export-oriented without establishing a domestic market; China exported 97.5% of its modules produced in 2006 and 96% in 2009 (IEA PVPS, 2010b).

As the PV industry slowed down faced with the European crisis, the continuous mass production from Chinese PV manufacturers created overcapacity issues (IEA-ETSAP and IRENA, 2013). Chinese PV manufacturers also encountered the difficult period due to lack of outlets for its production and the PV industry went through a restructuring process. The largest Chinese solar company, Suntech, filed for bankruptcy in March 2013 even though they received billions in direct loans from the Chinese Government (Bloomberg new energy finance, 2014).

Furthermore, China recently faced obstacles for imports of PV products going through trade disputes with the US and EU. It was thus observed that China started to delocalize the production lines to Taiwan (IEA PVPS, 2013) to avoid antidumping duties for Chinese solar products in the USA. The solar cell production in Taiwan has sharply increased to 8 GW in 2013 (IEA PVPS, 2014 applications). China needs to explore new avenues for market growth.

	Silicon (t)	Ingot/Wafers (MW)	Cells (MW)	Modules (MW)
2004		57		146
2007	1093		2600	2600
2010	45000	11000	10800	10800
2013	84600	29500	25100	25500

Table XLII: PV production in China (IEA PVPS China, 2011; 2012; 2013; IEA PVPS, 2013b)

2008	2009	2010	2011	2012
200,000	300,000	300,000	500,000	260,000

Table XLIII: Solar PV jobs in China (IEA PVPS, 2002 to 2014)

	2004	2007	2010	2013
Domestic sales (US$M)				23220
Exportations (US$M)	644	5252	25179	15759
Importations (US$M)	2063	3813	7264	8994

Table XLIV: Economic results from PV industry in China (UNCOMTRADE)

4.2.3 Installations: policy inputs and results (outputs and outcomes)

China's Solar PV power generation started in the 1960s but its dramatic progress is a recent event in the last 10 years (Zhao, et al., 2013). China's PV development started with the supply of electricity to off-grid rural areas.

The first political support to promote solar PV deployment was implemented through off-grid rural electrification programs; the Brightness Program (1996) and the Township Electrification Program (2000). The Chinese PV installation was driven by off-grid deployment to feed electricity in rural areas until the late 2000s, but the accumulated amount was relatively small; 140 MWp in 2008 (IEA PVPS, 2013b).

The serious rollout of policy instruments for PV deployment promotion started from the mid-2000s with the renewable energy law (REL) in 2006 (Xie, et al., 2012). Faced with a sharp rise in demand for energy consumption caused by the rapid economic development, China's energy policy mainly aims at securing a stable energy supply to balance its growing energy needs. China thus began to include sustainable development in its energy plan.

In 2007, China proclaimed the ‘medium- and long-term program of renewable energy development’ which aimed to increase its energy supply target using renewable energy sources up to 10% by 2010 and 15% by 2020 (Zhang & He, 2013). Chinese national PV installations reached a serious level in 2009 thanks to the national strategy of developing a domestic market (Grau, et al., 2012).

Since the late 2000s, China’s on-grid solar PV installations have rapidly increased based on the strength of the incentive programs to grid-connected rooftop and BIPV systems; e.g. central government subsidy programs such as the ‘Roof top Subsidy Program’ (2009), the ‘Golden Sun Demonstration Program’ (2009), and the ‘Solar PV Concession Program’ (2009) (Zhang, et al., 2013b; IEA PVPS China, 2011). In addition, faced with the diminishing demand from the European market, China needed to find a new market to absorb the excessive production. In 2011, the national FIT scheme started to support domestic PV market growth.

China contributed significantly to the global PV installed capacity; it became the largest installer representing more than 30% of the new installation capacity in 2013 (IEA PVPS, 2002 to 2014). China reached 18.3 GW of PV **cumulative installed capacities** in 2013, which accounted for around 14% of the global total output (IEA PVPS, 2014; EPIA, 2014). This nonetheless represents a small contribution to the **electricity generation**, amounting to 0.6% in 2013 and producing 25.6 TWh (Eurobserv’er, 2013b; IEA PVPS, 2014). Accordingly, its impact on reducing **CO2 emissions** is poor; rather it increases steadily every year from 4.1 in 2004 to 6.2 metric tons per capita in 2010 (The World Bank(b)). The **business value** of the Chinese PV installation market was estimated at US$ 23,220 million in 2013.

4.3 Conclusions of China case study

The Chinese policy started concentrating more on its industry development through export-driven strategies to increase its international competitiveness, rather than ensuring the energy transition. The PV sector obtained visible economic results, producing more than 60% of the PV cells for global needs in 2013, though with very tenuous outcomes in terms of the energy transition and climate change.

Furthermore, China still has a weakness when it comes to raw materials and equipment for the PV industry as it greatly depends on overseas production. Unlike the German pathway, China’s new energy plan aims at stimulating domestic demand through sustainable energy supply systems, which seems to be a timely solution to respond the PV industry slowdown.

Unlike Germany and Japan, Chinese PV development encouraged the industry first before it was decided to expand domestic installations to overcome the industry slowdown. China rapidly expanded its installations, thereby exceeding the market leader’s contribution. It is now expected that China will be one of the largest installers in the world in the next decades (EPIA, 2014).

5 Historic changes in PV policies of the U.S.

5.1 PV policy history: policy objectives and context

The U.S. has a long history of PV energy development mainly focusing on both supply-side and demand side. As seen, the U.S. is the pioneering country of PV technology. In the 1970s, the U.S. started to develop alternative energies to decrease the fossil fuel dependency. In response of the energy crisis in the 70's, the National Energy Act (NEA, 1978) was established to increase the country's energy security; NEA included the Public Utility Regulatory Policies Act (PURPA), which provided a legislative support for energy conservation as well as power generation from renewable energies. In this context, solar PV deployment in the U.S. was promoted (Go solar California; Martinot, et al., 2005)[69].

However, in the 1980s, the development of solar PV energy market slowed down facing with the oil price drop and the restructuration of the U.S. electricity market; the investment in the private sector was delayed due to the uncertainty of PV market (Martinot, et al., Op. cit.). In the 1990s, along with the increasing awareness of environment, some states seriously started to promote the use of PV energies. PV development was gained momentum through recently enacted the American Recovery and Reinvestment Act (ARRA, 2009) (U.S. Department of Energy (DOE))(Martinot, et al., Op. cit.); it is a policy package based on Keynesian macroeconomic approach for economic revival; it included job creation, infrastructures, and investment in renewable energies programs. This helps PV development focusing on both economic aspects (e.g. industry) and PV installations. However, the US energy policy is generally regulated at a state level; there is no specific target for PV at federal level (Burns & Kang, 2012). The country has a goal of 33% of retail electricity sales from renewable energy sources by 2020 (IEA, 2015c).

5.2 Policy inputs and results: supply and demand

5.2.1 R&D: policy inputs and results (outputs and outcomes)

The U.S. was the leading country in developing PV technologies in a long time. The federal support to the R&D for PV began with the space conquest during the 60's; PV cells were developed to give power to satellites (Dooley, 2008). As seen, the R&D support largely increased when the government looked for solution to reduce its energy dependency after the oil crisis of the 70's (Ruegg & Thomas, 2011). The US Department of Energy (DOE) manages the federal research on energy sector; it is the main source of funding for PV R&D. The budget for PV rose from about US$ 60 million in 1976 to almost US$ 350 million in 1980.

The National Renewable Energy laboratory (NREL) and the Solar Energy Research Institute (SERI) began their activities in 1977 (Ruegg & Thomas, Op. cit.). Their R&D programs focused on the **price reduction** by improving the **silicon production process** and PV technologies. The U.S. R&D contributed powerfully to reduce c-Si solar PV module price in the 1980s; in the periods 1976-1986, PV module price were reduced by 58$/Wp mainly driven by silicon price drop and R&D efforts

[69] Another important legislation for the promotion of renewable energies in the U.S. is the Energy Policy Act (EPACT, 1992), which aimed to increase clean energy use and improve overall energy efficiency.

(Gambhir, et al., 2014). In addition, fundamental R&D demonstrated a steady progress to develop non-silicon-based PV and breakthrough technologies.

However, the new government (1981) changed the policy priorities on energy towards other programs like the nuclear breeder reactors or synthetic fuel; the interest in PV thus declined. At the same time, the federal expenditures on energy R&D were cut by more than 50%.

In the 1990s, along with the PV cost drop, the increasing concerns on climate change and acid rains drew the national interest into PV sector. Since then, R&D programs mainly attempted to lower the costs, to improve the efficiency and to increase social acceptance of the PV technology; they mainly focused on PV manufacturing and thin film technologies (Ruegg & Thomas, 2011; IEA PVPS USA, 2002; 2003; 2004).

In 2006, the Solar America Initiative (SAI) was launched. The target was to decrease the costs of PV to make solar electricity more competitive compared with other conventional energies by 2015 (U.S. Department of Energy, 2008). The program aimed to implement the energy transition in southwest region of the country, in populated state with **high solar resources** (U.S. Department of Energy, 2008b). The R&D focus concerned PV technology[70], the concentration solar power, the system integration and the market transformation (IEA PVPS USA, 2009). In addition, establishing a partnership among public research center, universities and firms was also highlighted. The federal budget for PV R&D has steadily grown since then (see Table XLV).

In 2011, the SunShot Initiative replaced the project. By funding solar PV R&D to reduce the PV power cost (being competitive without the political support), the country attempted to increase the share of PV power in the country energy mix to 15%-18% by 2030 (IEA PVPS USA, 2011). Since 2009, the DOE gave a priority to support in defensing the national PV industry from the cheap Chinese products.

In conclusion, continuous R&D efforts allowed USA to keep its leading position in the solar PV R&D. Table XLV illustrates the consistent **R&D investment**; US$ 268 million was allocated in PV R&D in 2013. In addition, as Table XLVI displays, the US has consistently an important share in the global **patents** of PV technologies since the 1980s (see Table XLVII).

US$M	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
USA	35	65.7	86	75.8	121.8	138.3	122.5	145	172.4	222.9	262	268.7

Table XLV: Federal R&D budget in the US (IEA PVPS, 2002 to 2014)

Patents: cell & modules	1995	2000	2004	2007	2010	2013	Patents: silicon refining	1995	2000	2004	2007	2010	2013
USA (%)	11.4	10.1	10.8	11.3	14.4	13.5	USA (%)	10.1	8.1	6.5	5.4	7.5	7.4

Table XLVI: Patents for cells & modules and patents for silicon refining in the US (Unit: cumulative % of the global patents) (Espacenet)

%	1980s	1990s	2000-2004	2005-2009	2010-2011
USA	60%	37%	32%	32%	22%

Table XLVII: US Patents application filed under the PCT (OECD.Stat)

[70] Incl. basic research in thin films and future technologies

5.2.2 *PV industry: policy inputs and results (outputs and outcomes)*

The US PV industry has grown in line with the development of PV technology. The country was the global market leader until the 1990s (Martinot, et al., 2005), it accounted for 44% of **market share** in 1996. However, its market share was taken by Japan and Germany from the end of the 1990s. The PV industry in Japan and Germany has largely advanced supported by a domestic growth of PV installations (Greenpeace, 2001).

In 2002, the US was the second PV cell producer in the world after Japan with 22% of the global cell production (121MWp). In 2005, the country was placed in fourth in global cell production after Japan, Germany and China; it had less than 9% of the share in the global market with 156 MWp of production.

In 2006, the Solar America Initiative (SAI) started aiming at increasing PV installations and boosting PV industry. Accordingly, the production of PV products has rapidly increased to supply the national demand. PV module production has almost doubled from 139 MWp in 2004 to 266 MWp in 2007. However, the national production was never able to fulfill the domestic demand. The country had to import PV products to some degree, thus the **PV exportation** stayed lower than the PV importations (Table L).

At the end of the 2010's, Chinese products beat the US PV industry (e.g. cell and module production). However, the US still has much competitiveness over solar-grade silicon making based on high standards of knowledge and long-standing expertise. USA has the largest producer (Hemlock) of solar-grade silicon. In addition, the US also benefited from its strong electronic industry; in 2004, about 10% of the silicon used in the PV industry was residual silicon from the electronic industry (IEA PVPS, 2004). Along with the rapidly increasing global demand of PV products, the US silicon industry has increased. Furthermore, as seen, China had a limited capacity in producing solar-grade silicon; Chinese PV firms imported large amounts of silicon from the US. In 2013, the USA remained one of the world leaders in this sector by producing about 40000 t.

Trade balance (US$M)	2004	2007	2010	2013
USA	415	1565	2459	1144
China	-4	-1116	-2489	-1487

Table XLVIII: Comparison of trade balance of USA and China for solar- grade silicon (UNCOMTRADE(b))

According to the US' energy policy, PV industry is considered as future business for the country; it brings a growth engine in the US economy and creates jobs. In 2009, the American Recovery and Reinvestment Act (ARRA) proposed a loan guarantee of US$ 16.1 B, under the DOE loan guarantee program, to promote renewable energies. It targeted large-scale installations of new technologies (e.g. 37% for CSP) and PV projects (38%), and PV manufacturing (8%) (Bloomberg New Energy Finance, 2013). Furthermore, there was 30% investments tax credit for PV firms.

However, in spite of such political support, the US industry turned to a low growth phase after China began to increase the investment in PV R&D and expand its production capacity (IEA PVPS, 2002 to 2014). The US had a peak **production of module** with 1.3 GW in 2010; however, it declined to 988 MW in 2013. Despite of a slowdown of PV manufacturing industry, the **number of PV jobs** rose quickly mainly supported by the high growth of PV installations from 2008 (Table L).

	Silicon (t)	Ingot/Wafers (MW)	Cells (MW)	Modules (MW)
2004	5100	181	138	139
2007	5100	142	266	266
2010	42561	624	1133	1277
2013	39988	103	478	988

Table XLIX: PV production in the US

	2004	2007	2010	2013		2004	2007	2010	2013
PV jobs (x1000)	10.9	8.19	102	143	Domestic sales (US$M)		1367	4977	13700
Importation (US$M)		2156	4412	5791	Exportation (US$M)		1914	3250	2243

Table L: Economic results from PV industry in the US

It is worth reviewing that some US firms commercialized thin film technologies. From 2007, the commercialization of thin film PV modules became visible thanks to accumulated skills developed by various R&D programs. They represented an important share of the country's module production (IEA PVPS, 2002 to 2014). The US became the biggest producer of thin film modules; First solar is the virtual monopoly of the CdTe technology. However, thin film technologies also suffered from the global PV overproduction and the rapid drop in c-Si module price. The production started to slow down from 2010 (Table LI) and US thin film firms delocalized their production lines, mainly in Malaysia.

Thin film production (MW)	2004	2007	2010	2013
The US	20	189	484	372

Table LI: Thin film module production in the US

In addition, the US government recently implemented trade barriers to protect its PV industry. The federal government decided to penalize foreign manufacturers for anti-competitive behavior. It mainly concerns Chinese manufactures; in 2012, the US International Trade Commission ruled that Chinese competitors (anti-dumping) harmed the domestic industry of PV cell manufacturing. It was decided to impose countervailing duties on Chinese-manufactured cells (Bloomberg New Energy Finance, 2013).

5.2.3 *Installations: policy inputs and results (outputs and outcomes)*

The US energy policy aimed to increase renewable energies such as PV to diversify its energy sources and to protect the environment. However, the US market is fragmented with different PV installation environments. PV policies depend on the political choice of states government; each state has a different policy and legal conditions, which engender different PV system prices (Seel, et al., 2014; Steward, et al., 2014). Many state governments enacted policies to stimulate PV installations. Since the mid-2000s, the US installation has been rapidly increased mainly supported by subsidized programs paid by states government.

California has been playing a leading role in such PV installation growth in the US; for example, 70% of all PV installations in the US came from this state in 2007 (IEA PVPS USA, 2007).

California also showed the high load in reducing GHG emission[71]. It is the largest distributed PV market in the US. For example, California Solar Initiative (CSI) program[72] was implemented in 2007 to provide incentives for PV system installations; it has a budget of $2.167 billion over 10 years, and the goal is to reach 1,940 MW of installed solar capacity by the end of 2016 (Go Solar California(b)). In 2012, the CSI represent 80 % of all California residential installed capacity, and 32 % of all U.S. residential installed capacity (IEA PVPS USA, 2012). The successful increase in PV installations in California came from a mix of good weather condition, high electricity prices (U.S. Energy Information Administration (EIA), 2016) and supportive governmental incentive program.

Table LII displays major demand-side policies in the US. The tax credit (30%) at the national level and RPSs at the state level are key drivers for PV growth in the US (IEA PVPS USA, 2014). In addition, 21 states rolled out PV requirements in RPS (a portion of RPS should be met by PV power supplies)

Supporting measures	Notes
FIT for grid-connected applications	Conducted by 6 states
Capital subsidies[73] for equipment or total cost	Federal: 30 % investment tax credit State: at least 22 states have it
Renewable portfolio standards (RPS) [74]	29 states
PV requirement in RPS	21 states
Income tax credits	Federal: 30 % for residential, commercial, and utility systems 19 states for solar projects
Prosumers' incentives	Self-consumption, net-metering, net-billing (44 states)

Table LII: Major demand-side policies in the US

California RPS was established in 2002 and went through a number of amendments; it now aims to supply 50% of the electricity using renewable energies in 2030 (DSIRE, 2015). State RPS encourages more growth of PV system installations as the requirements for renewable energy additions increase each year.

In 2004, the US had only 149 MW installed capacity mainly driven by grid-connected distributed systems. However, the **cumulative installed PV capacity** in the U.S. was 12 GW in 2013. In addition, grid-connected centralized (utility-scale) system showed steady growth over the last decade and now gained the visibilities in the US market; in 2014, more than 50% of the PV installed capacity is grid-connected utility-scale systems.

In 2014, the **PV electricity production** in the US accounted for 0.61% of the total electricity consumption, producing 23 TWh (IEA PVPS USA, 2014). The **business value** in the U.S. was US$ 16.4 billion in 2004.

US	2000	2004	2007	2010	2013
Cumulative PV installations (MWp)	-	131	427	2022	12022

Table LIII: Cumulative PV installations in USA

[71] California began enforcing a cap and trade program in 2013, which aims to cut GHG emissions by 16 % by 2020.
[72] It has fully depleted or is in the tail-end of many of programs.
[73] Direct financial subsidies aimed at reducing the up-front cost barrier, either for specific equipment or total installed PV system cost.
[74] (Wang, 2014; Lawrence Berkeley National Laboratory, 2013)

5.3 Conclusions of the U.S. case study

The US's PV development has conducted with a well-balanced focus placed on R&D, industry growth and PV market diffusion. The US has frontier technologies in the PV sector for a long time. It gives a technological helps to develop the PV industry combined with policy supports. However, the country's energy policy is drive by state governments. PV deployment pattern and outlook differ from one state to another state. However, the policy direction by the present federal government aims for increasing renewable energies in the future electric power mix and solar PV development has a promising future in the country. Furthermore, the PV policy focus on economic growth is obvious; the country wants to create more jobs in this sector to bring economic growth. However, the actual participation in energy supply using the solar PV still has room to grow.

In addition, US market has a challenge to deploying PV systems; PV system installations have different permission practice and regulatory requirements across the country under different jurisdiction. The lack of standardization can be a barrier for a large-scale deployment of PV systems (IEA PVPS USA, 2014).

6 Historic changes in PV policies of France

6.1 PV policy history: policy objectives and context

France is a pioneering country of PV technology development since French physicist, Alexandre Edmond Becquerel, first observed the photovoltaic effect in 1839 (Ricaud, 2013). Like many other countries, facing the oil crisis in the 1970s, France started to worry about the energy security and seriously developed alternative energies to reduce the dependency of fossil fuels. French energy policy to increase the energy security was mainly focused on nuclear power and renewable energies (Méritet, 2011). After the second oil crisis, nuclear power became the main source of electricity in France and research on renewable energies was reduced, as they are more costly and less profitable (Planete energies, 2015).

France emits the least GHGs compared with its neighbors due to an important share of nuclear power in the electricity generation. Therefore, combating GHG emission was not prime reason to increase solar PV power in France; PV systems were used for rural electrification. And then, the initiative of combating climate change became a significant issue in French energy policy based on the engagement with the Kyoto Protocol and EU energy directives. The country proposed a quite ambitious target of reducing CO2 emissions; a 75% reduction in CO2 emissions by 2050 (IEA, 2009).

There are several legal aids to develop Renewable energies including PV power; e.g. the Energy law (2005), creation of a new energy and environment ministry (MEEDDM, 2007[75]), the

[75] Ministère de l'Écologie, de l'Énergie, du Développement durable et de la Mer (MEEDDM), it is now called the « Ministère de l'Écologie, du Développement durable et de l'Énergie »

Grenelle law (2009)[76], and the Energy Transition Law (2015). The Energy Transition Law[77] aimed to increase electricity generation using renewable energies to 40% in 2030 and reduce GHG emissions by 40% in 2030 compared to 1990 level (Enerdata, 2015; Renewables, 2015). PV had a negligible visibility in the country's electricity mix until the mid-2000s before the government launched an attractive financial support (FIT) for grid-connected PV systems.

French PV development was first focused on technology development, and then the deployment of PV systems earnestly started based on the governmental institutional (permission of grid-connection) and financial (FIT) support. Such policy supports are mainly driven by the political strategies towards a sustainable growth. However, the policy focus on PV industry was behind other initiatives until a recent date.

6.2 Policy inputs and results: supply and demand

6.2.1 R&D: policy inputs and results (outputs and outcomes)

France has a leading role in developing the PV technology. Like in the US, the development of the research on PV in France began early in the 1960s with the space exploration[78]. In 1970, France started to focus on renewable energy research as part of its policy to increase energy independency. In 1974, France was the first country to implement a R&D public policy across all the solar PV technologies (including PV systems, silicon-based technologies, thin film, concentration and other new concepts). In the late 1970s, CNRS[79] made great strides in solar power, solar furnace chemical reactions and PV (Planete energies, 2015). However, the technology had to improve their efficiency for commercialization. At the end of the 70's, France was a leading country of PV technologies in Europe.

In the 1980s, the research on renewable sector slowed down as the sector was less profitable than other energy technologies; e.g. the national resources were more concentrated on nuclear power. In 1981, the new government gathered the research on new energies in a single agency (AFME[80]) and the PV research lost its visibility (Ricaud, 2013). During this time, PV technology was highlighted as a solution to power isolated areas.

Since the late 1990s and early 2000s, ADEME, CNRS and CEA[81], began to conduct further PV researches to reduce the costs and increase the performance (IEA PVPS France, 2002). In 2005, the national research agency (ANR) and the state-owned company OSEO[82] were created to promote public-private partnerships; this helps connect PV R&D to PV industry. In collaboration with ADEME, ANR annually put out a call for proposals in several sectors of the PV value chain.

[76] The Grenelle law set a foothold for developing technologies of clean energy with objective for reducing emissions in the building and transports (CO_2 reduction to the level of 1990 in 2020), for developing renewable energies (23% in 2020) and for giving more funds in energy R&D. (Ministère de l'Ecologie, du Développement Durable et de l'Energie)
[77] Loi relative à la transition énergétique pour la croissance verte.
[78] During the 60's, the French space agency CNES (Centre National d'Etudes Spatiales) worked on the development of the PV technology.
[79] Centre national de la recherche scientifique.
[80] It was AFME (Agence Francaise pour la Maîtrise de l'Énergie) and it is now called ADEME (Agence De l'Environnement et de la Maîtrise de l'Energie).
[81] Commissariat à l'Energie Atomique
[82] It aims to promote innovation and to support SMEs to bring economic growth engines and to create jobs.

In 2006, the national solar energy institute (INES[83]) was created to conduct research on PV to improve all sectors across the PV value chain (IEA PVPS France, 2006; INES); it also aims to build a close link between pure research and applied research. Since the mid-2000s, INES[84] and IRDEP (EDF) mainly lead the R&D on PV in France (Direction Générale de l'Energie et du Climat). In 2013, IPVF (Institut Photovoltaique d'Ile de France) (IPVF) was created to improve performance and competitiveness of PV cells and modules through synergies based on an industrial-academic partnership (IEA PVPS, 2013).

The **budget on R&D** in France stayed quite constant since the early 2000's (see Table LIV). In spite of tight budget, France managed to study various sectors such as all the PV technologies, PV applications, and the entire value chain to support PV industry (IEA PVPS, 2010). According to OECD data on patent applications filed under PCT[85] (OECD.Stat), France kept a constant contribution to the world patent; it accounts for more than 3% of the world **patents** from the early 90's up to date (Table LVI). However, the decrease of French contribution to the patent of silicon refining is also visible (Table LV).

US$ M	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
France	9.237	5.763	9.4	15.4	32.8	12.3	17.6	57.2			128	

Table LIV: R&D budget in France (IEA PVPS, 2002 to 2014)

Patents: cell & modules	1995	2000	2004	2007	2010	2013	Patents: silicon refining	1995	2000	2004	2007	2010	2013
France (%)	2	1.5	1.5	1.6	1.6	1.7	France (%)	4.5	3.6	2.9	2.2	1.7	1.4

Table LV: Patents for cells & modules and patents for silicon refining in France (Unit: cumulative % of the global patents) (Espacenet)

	1980s	1990s	2000-2004	2005-2009	2010-2011
France (%)	1.9%	3.6%	3.5%	3.2%	3.1%

Table LVI: French patents application filed under the PCT (OECD.Stat)

6.2.2 PV industry: policy inputs and results (outputs and outcomes)

The French PV industry began early mainly driven by two leading PV firms; France-Photon and Photowatt[86]. Photowatt started manufacturing crystalline silicon PV cell and modules since 1978 (ADEME, 2002). After a good start, the two companies suffered from the oil price drop in the 80's and French government's choice to focus on nuclear power (Ricaud, 2013).

Since then, French PV industry has developed somewhat supported by the government's political aids. For example, there was a tax exemption (1995) for PV industry and subsidies to SMEs[87]. A number of French firms manufactured PV products across the whole value chain. In the 1990s and 2000s, Photowatt[88], a vertical integrated manufacturer of crystalline silicon materials, has taken the lead in developing PV manufacturing in France. In 2002, the company had a production cell capacity

[83] Supported by CEA and Savoie University
[84] France's center of reference in the field of solar energy, it was set up with the backing of Savoie Départemental Council and Rhône-Alpes Regional Council, and includes research and development teams from the CEA, CNRS, University of Savoie and CSTB.
[85] The Patent Cooperation Treaty
[86] A subsidiary of big electronic companies, Philips and CGE (L'Usine Nouvelle, 2012)
[87] FIDEME special fund for subsidies granted to the SMEs was implemented in 2002
[88] It was taken over by a Canadian company in 1997

of 25MW (3% of the global capacity, 11% of the European capacity). It focused on high quality PV modules offering a 25-year warranty on its module. It is also interesting to notice that French firm also developed and commercialized PV products to adapt the building integration (e.g. roof tiles integration, façade integration) (ADEME, Op. cit.).

However, in the 2000s, French PV industry failed to benefit from the global PV market growth; its expansion of production capacity was unsuccessful (see Table LVII). In fact, many industrial projects for PV production were at demonstration level and investments on new factories were largely dependent on the governmental support (IEA PVPS, 2006; 2007; 2008; 2009). French PV industry quickly lost its market share in the fierce competitive global market.

It is worth remarking that French PV industry has declined while the PV installations in France sharply rose due to FIT support in the 2000s. For example, the annual installations reached a peak with 1760 MW in 2011. However, at the same year, the French PV industry was on a downturn and Photowatt[89] went bankrupt (IEA PVPS, 2011). The lack of policy continuity is one failure factor; for example, the French moratorium on FIT gave a negative signal to investors causing a decrease of investments in PV sector (Le monde, 2011). Even though French PV firms have a wide range of PV business areas across the value chain, French PV industry is quite fragile due to the weak competitiveness and lack of policy support and financing.

PV sector created 9044 **jobs** in 2014; 544 jobs related to public R&D and 8500 jobs from PV industry across the value chain (IEA PVPS, 2014). French PV industry had a 600 MWp **production capacity of PV modules** in 2013 with the global market share of around 1%. In addition, **domestic PV sales** were US$ 925 million in 2013 and **PV export** amounted to US$ 408 million in 2013.

	Silicon (t)	Ingot/Wafers (MW)	Cells (MW)	Modules (MW)
2004	285	33	30	36.5
2007	570	40	40	50
2010	680	70	71 (capacity)	525 (capacity)
2013	300	80	135 (capacity)	600 (capacity)

Table LVII: PV production and PV production capacity in France

	2007	2010	2013
Jobs (x1000)		24.3	12.13
Domestic sales (US$M)			925
Exports (US$M)	268	636	408

Table LVIII: Economic results from PV industry in France

6.2.3 Installations: policy inputs and results (outputs and outcomes)

France's demand-side policies to stimulate PV installations in France can be divided into 2 stages: promoting rural electrification via off-grid systems since the 1980s (IEA PVPS France, 2002) and then supporting grid-connected PV systems since 2002.

The first main stream of PV usage was off-grid PV system. Since the 1980s, off-grid PV systems was used by EDF (ADEME, 2002) for rural electrification; they were used for the isolated areas in continental France, Corsica and French overseas departments, where grid extension is more

[89] Photowatt/EDF ENR PWT, is now owned by EDF ENR since March 2012 (IEA PVPS, 2014).

expensive than the PV solution. The collaborative agreement signed between ADEME and EDF in 1993 supported financially this solution through FACÉ public fund (ADEME, Op. cit.). There were other financial supports to simulate off-grid systems; e.g. subsidies from ADEME, EDF and Regional Councils[90]. The government set income tax exemption contracts aiming to reactivate economy in the overseas department. In 2002, the **total cumulative installed capacity of PV** was 17.2 MW and 89% was off-grid systems in France (61%) and its oversea department (28%).

The second stage of PV demand-side polices was focused on grid-connected systems. In 2002, a FIT was first implemented. However, its effects were negligible due to unprofitability of the tariffs. In the mid-2000s, grid-connected PV systems became visible in French PV installations along with permission of grid access, establishment of metering system and financial incentives (e.g. tax credit, FIT); it accounted for more than 50% of the total cumulative installed capacity of PV in 2006 (IEA PVPS France, 2006). The demand-side policies to stimulate PV system deployment included tax credit, financial contribution from regional and departmental councils, and FIT funded through the CSPE tax. The market demand has increased as the financial support more strengthened.

In addition, the new FIT implemented in 2007 attracted new investment in PV installations; grid-connected PV system accounted for 70% of the total cumulative installed capacity of PV in France by the end of 2007. In particularly, the French governmental support aimed to boost BIPV providing higher FIT in this sector; the strategy is to bring innovation in architectural integration (PV became the construction material in the long-run) (IEA PVPS France, Op. cit.). However, French FIT went modified several times confusing investors; in December 2010, the government announced a 3-month moratorium on FIT[91] allocation because of the financial burden (FIT impacts on CSPE) (CIRED, 2012).

The new energy transition law demonstrated an obvious political will to increase renewable energies and solar PV is one of the promising technologies to realize the national objectives. Accordingly, France raised its PV target to 8 GW (SeeNews Renewable, 2015) by 2020 from 5.4 GW proposed by the Grenelle law in 2009 (L'echo du solaire, 2015).

Important political supports on PV deployments are illustrated in Table LIX (IEA PVPS France, 2014). It is interesting to notice that France’s regional and departmental authorities also conduct PV promotion policies. The French installation growth was mainly driven by FIT and calls for tenders (IEA PVPS France, 2014).

	Supporting measures
National policy	FIT for grid-connected applications (FIT < 100kW, call for tenders > 100kW)
	Off-grid systems: public FACE fund for rural electrification
Regional authority (call for proposal)	Capital subsidies for equipment or total cost
	Prosumer’ incentives (self-consumption)

Table LIX: Political supports to PV deployments in France

[90] They were allocated to PV systems in rural area not falling under the FACÉ fund, and tax exemption contracts for PV systems in the overseas department.

[91] In December 2010, the French Government decided to suspend the purchase obligation, which applies to photovoltaic installations above 3 kWp. The moratorium ended in March 2011 with the publication of a new FiT decree, which applies to all PV systems up to 12 MWp. (Keep On Track, 2013).

French FIT is financed by the Contribution to Electricity Public Services (CSPE); in 2014, the charge of CSPE was 16, 50 €/MWh and [92]the total sum to support PV sector amounted to around € 1,990 million for the year 2014 (IEA PVPS, 2015).

€M	2007	2008	2009	2010	2011	2012	2013
Support for PV (CSPE)	1.1	7.8	54.3	208.9	794.9	1 683.2	1 919.9

Table LX: Annual support to PV through CSPE (Cour des comptes, 2012; CRE, 2011 to 2013)

The country's cumulative **installed PV capacity** was 5.6 GW (IEA PVPS France, 2014) at the end of 2014; grid-connected distributed systems accounted for 70% of it. In 2014, PV systems in mainland produced 5.9 TWh of electricity; it accounted for 1.3% of the national power demand (**share of the national power supply**) (SeeNews Renewable, 2015). However, **the effect on CO2 emission reduction** is not significant because the country already has a low-carbon electricity mix with nuclear power.

France	2000	2004	2007	2010	2013
Cumulative PV installations (MWp)	-	26	81.5	1194	4733

Table LXI: Cumulative installations in France

6.3 Conclusions of France case study

French PV development started with a focus on technology development. PV industry has successfully started in the country based on its technology competitiveness gaining an important share in the global market. However, French PV industry lost its visibility in the global PV market over the last decade. Since nuclear power is the major source of electricity, the country had little demand in developing solar PV to increase energy independency or combat climate change. This explains why France used PV systems to power economically some rural or isolate areas.

The current energy policy that focuses on energy transition and reducing GHG reduction provided a favorable condition for PV development in the country. Over the last several years, PV installations have rapidly increased based on attractive FIT and permission to the grid. It is also notable that the country has put efforts to develop BIPV system.

French PV policy has a more focus on R&D efforts and PV installations rather than PV industry aspect. However, PV industry development enables to boost the national economy (e.g. job creation or exports). The European PV industry suffered from the fierce price competition driven by Chinese producers. French PV industry can target niche market that the country has a high competence to develop PV industry in the future; e.g. building integration and coupling PV systems with electric cars.

[92] The total sum for ENR support amounted to around 2, 200 MEUR for the year 2014.

7 Historic changes in PV policies of South Korea

7.1 PV policy history: policy objectives and context

South Korea's energy consumption has sharply increased since the mid-1970s to support its rapid industrialization, however, the country's economy heavily depends on overseas fossil fuels; the country imports 97% of its energy supply mainly from Middle Eastern nations. After the two oil crises of 1973 and 1979, the pursuit of energy security was the pivotal initiative of energy policy in South Korea. Since then, the New and Renewable Energies (hereafter NRE) began to receive attention as alternative energy sources to fossil fuels. The solar PV was chosen as one of the national major initiatives of development of alternative energies starting in the 1970s.

The country snapped into renewable energy policies at the national level by enacting the Promotion Act on Alternative Energy Development in December 1987. In 2008, the government got down to the national energy transition by announcing the 3rd Basic Plan for New & Renewable Energy Technology Development & Dissemination (2009~2030); NRE will meet South Korea's primary energy up to 11%, and 20% by 2030, and 2050 respectively. In addition, the plan also aims to reduce greenhouse gases with sustainable growth (20 % GHG reduction by 2020). More importantly, the concept of green growth has a crucial role in this plan; it aims to bring new growth opportunities through green technology development. PV technology is an important initiative to stimulate the country's economic growth focusing on technology development, expanded domestic production as well as promotion of export. Under this plan, South Korea's policy strategy gave a well-balanced focus on PV development on R&D, industry and PV installation diffusion.

7.2 Policy inputs and results: supply and demand

7.2.1 R&D: policy inputs and results (outputs and outcomes)

South Korea has initiated R&D in solar PV technology focusing on basic research in the 1970s. They were mainly conducted in the laboratories of universities (Ministry of Trade, Industry and Energy of South Korea, 2013). In 1988, a full-scale R&D activity started, supported by the Promotion Act on Alternative Energy Development, which was enacted in 1987 for the technology development of NRE; solar PV was considered as a key technology (with wind power and fuel cell), thanks to its greater spread effect to other industries. Since then, continuous efforts have been made to advance the national competitiveness in the PV technology and commercialization[93].

The country's R&D investments in PV follow three stages with the series of three Basic Plans for NRE development since 1988. The first stage (1988-2002) opened the beginning period of the large scale R&D with a focus on the technological catch-up to improve the performance of the solar cells for a practical use and to find solutions for mass production. The second stage (2003-2007) aimed at the technological progress for the commercialization through the development of low-cost and high

[93] From 1988 to 2011, South Korea has invested US$ 2.5 billion in various R&D projects of 11 technologies of new & renewable energies (solar, wind, fuel cell, IGCC, hydrogen…) and the government investment accounts for 59% of the total investment. During this period, the government allocated 33% of total investment into Solar PV with US$ 377 million; the total investment in solar PV was US$ 568 million (66% of government's support, 34% of private investment) (source: New & Renewable Energy White Paper (2005, 2009, 2010, 2011), Ministry of Trade, Industry and Energy, South Korea).

efficiency cells. The third stage (2008-2011) concentrated on increasing the international competitiveness and on R&D in non-crystalline silicon technologies. The country's PV policy aims to stimulate R&D in both the public and the private sector to create the domestic market. The investment in PV R&D has risen in each plan with a total cumulated public investment of US$ 377 million in 2011 (Ministry of Trade, Industry and Energy of South Korea, 2005, 2009, 2010, 2011). Furthermore, the private sector's efforts became more significant in PV R&D.

South Korea's research efforts concern various technologies of PV with a balance in both present and future technologies (Hyundai Economy Research Institute and MKE, 2013). Private companies invest more in silicon-based solar cell technologies while research in non-silicon-based or non-mature technologies for commercialization is mainly driven by public organizations.

In conclusion, South Korea demonstrated consistent efforts to develop PV technologies; the steady increase of **R&D investments** supports the country's R&D strategies. In 2012, US$ 118 million was allocated for PV R&D. The results can be measured with **patents** in PV technologies. The country's contribution to the global patents has shown a constant growth since the 1990's; it became one of the major countries with advanced PV technologies of both cell/modules and silicon refining.

US$ M	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
S. Korea	3.2	4	6.9	5.9	19.7	18.4	52.8	55.4	72.6	93.9	118	-

Table LXII: R&D Budget in Korea (IEA PVPS, 2002 to 2014)

Patents: cell & modules	1995	2000	2004	2007	2010	2013	Patents: silicon refining	1995	2000	2004	2007	2010	2013
S. Korea (%)	0.4	0.5	0.7	1.5	4.5	8.4	S. Korea (%)	0	0	0.2	0.2	0.8	2.2

Table LXIII: Patents for cells & modules and patents for silicon refining in South Korea (Unit: cumulative % of the global patents) (Espacenet)

	1980s	1990s	2000-2004	2005-2009	2010-2011
S. Korea (%)	0%	0.7%	1.1%	6.1%	9.3%

Table LXIV: South Korean patents application filed under the PCT (OECD.Stat)

7.2.2 PV industry: policy inputs and results (outputs and outcomes)

The government has prioritized PV sector and made continuous investments into the technological development since 1988 to make it more economically viable. This is a strategic decision to seek for synergies among industries. South Korea has a strong manufacturing capacity, in particular, in the field of manufacturing of LCD, memory chips and smart phones in the global market. Since PV industry uses similar technologies as the semiconductor and LCD industries, the country took the strategic position in quest of synergies effects coupled with existing industry knowledge and infrastructures represented by conglomerate Samsung, LG, and Hyundai. [94]

The country's PV policy strategy aims to create the domestic market first and then increase overseas export. During the green growth plan, PV was highlighted as export-led industry due to its industrial capacity and market maturity.

The supports to the PV production are taken in forms of **loans and tax incentives**. The government provides long-term and low-interest loans to the manufacturers of solar PV equipment and

[94] MKE's reports, Seoul, South Korea, 2010

module manufacturers to promote the commercialization of large-scale facilities; it reduces the burden of initial investment cost[95]. Those supports started from the early 1980s, but the amount was negligible until the mid-2000s. It started to play an important role in inciting the PV industry as the solar PV market evolved.

The accumulated loans for PV production until 2011 are US$ 310 million. Loans are primarily intended to support to the SMEs providing up to 90% of the total cost (up to 50% for large sized firms), and the interest rates are variable quarterly. Furthermore, there are tax incentives with 20% of income taxes and corporate taxes deductions for the manufacturers who produce PV equipment and materials (KOPIA).

The evolution of the production was quite slow until 2007 but South Korea had a solid manufacturing capacity in silicon with its competency in electronics. Since 2008 with the green growth plan, a significant increase in the production of solar PV has been observed. South Korea's PV production capacity has experienced an important expansion covering the whole value chain. The increased demands in domestic installations were mostly met by the domestic production, not by the importations. Until 2007, the created domestic market was the outlet of PV products and then the country became more capable to export those products from 2008.

The PV growth gives a positive impact on South Korea's economy; **the number of companies** has doubled every three years since 2004 and the **employment** achieved a twenty-fold increase (KEMCO). The **sales in PV** have also risen since 2004; in 2010, the **domestic sales** were US$ 8 billion and **exports** amounted to US$ 4.5 billion.

	Silicon (t)	Ingot/Wafers (MW)	Cells (MW)	Modules (MW)
2004			2.4	
2007	6523	150	25	53
2010	20000	800	770	925
2013	40000	1800	1000	1700

Table LXV: PV production/ PV production capacity in South Korea

	2004	2007	2010	US$ M	2004	2007	2010
Jobs (x1000)	0.7	3.7	13.7	Domestic sales	143	1249	8078
Numbers of PV firms	49	101	212	Exports	64	625	4535

Table LXVI: Economic results from PV industry in France in South Korea

7.2.3 Installations: policy inputs and results (outputs and outcomes)

South Korea's deployment of solar PV has a relatively short history in comparison to the PV installation evolution of other leading countries. Until 1996, South Korea had a negligible accumulated installed capacity of PV with 2 MW (IEA PVPS Korea, 2002 to 2011) due to high cost of the PV installation as well as a lack of market preparation and publicity.

In 2003, the government suggested a specific solar PV diffusion plan through the 2nd Basic Plan for New & Renewable Energy Technology Development & Dissemination. In this context, the

[95] Those loans exclude consumables products, materials and equipment which can be used in other industries (e.g. bearings...), as well as land purchase or construction costs.

FIT system[96] for NRE has been launched in 2002, and the solar PV sector has started receiving FIT support from 2004 (Shin, et al., 2008). In addition, various policy instruments were launched to stimulate the domestic installations; e.g., one million green home project, the mandatory use in public buildings, and national subsidies. However, they targeted a restricted area while the FIT system covered all kinds of connected PV systems, from small rooftop system to large centralized power plant. The FIT was the major driver of the national installation with a peak in 2008. However, it defined a fifteen or twenty year involvement and became a financial burden to the country. South Korea's government has thus ended it and decided to implement a quota system (RPS) to promote large-sized PV power plants.

South Korea has demonstrated a rapid increase in PV installations. The **accumulated installed capacity** exceeded 35MW in 2006 and reached almost 1.5 GW in 2013. South Korea's photovoltaic power generation stayed anecdotal until the 3rd Basic Plan; it only produced 71 GWh/year in 2007. With the launch of the plan, the production has increased quickly, reaching 917 GWh/year in 2011. The PV power reached 13.1% of the NRE power generation in 2010 (Ministry of Trade, Industry and Energy of South Korea, 2005, 2009, 2010, 2011). The absolute capacity is still very small compared to the total power generation in South Korea with about 0.4% of the domestic production (**share of the national power supply**) in 2013. Thus, the impact on the energy transition is quite negligible. Even though South Korea demonstrated a rapid progress in the PV sector with full-scale support, the impacts on the energy transition are fairly marginal, taken national absolute values into account.

South Korea	2000	2004	2007	2010	2013
Cumulative PV installations (MWp)	4	8.5	81.2	650	1467

Table LXVII: Cumulative installations in South Korea

7.3 Conclusions of South Korea case study

South Korea is now exceeding 1.5 GW of PV installations from nearly little installation in the mid-2000 with the successful launch of its PV deployment. The rapid growth is mainly due to the combined policy mix that covers both the supply and the demand aspect.

Selected as one of the core sectors in renewable energies linked with the existing technological competency aiming at securing synergy effects, South Korea rolled out the successful start in the development of solar PV technologies with the support of the government's full-scale policies. Furthermore, the nation's dynamic economies with a solid financial status helped realize PV initiatives throughout extensive investments from public and private sectors. The combined policy set of supply-side and the demand-side supports helped to increase both the nation's industry capacities and domestic installations, and eventually boost the national economy.

However, South Korea's PV development has its barriers and limits. Even though South Korea achieved a rapid increase in domestic installations in PV over the last decades, its photovoltaic

[96] In 2002, the Act was amended to expand its scopes of the support for mass deployment of renewable energies and a Feed-in-Tariff (FIT) was included (2002-2011).

power generation is still negligible for the high-energy consuming country. In addition, the solar PV increase is still mostly dependent on the public support. However, the FIT, the major driving force to the PV deployment has finished in 2011 with the replacement by RPS. Thus, the implementation cost will pass on to generators, but the PV is not yet economically feasible in South Korea. In this regard, South Korea encounters a dilemma in attempting to raise the solar PV production as it has a fundamental subject relate to the electricity pricing system. South Korea's electricity charges (industry, residential) are quite below OECD's averages (IEA, 2012).

8 Conclusions

This chapter conducted a retrospective analysis of PV policy mechanisms using a schematic map proposed by author. The macroscopic tool has its own significance because it helps decision makers or evaluators to have a big picture of PV policy system based on the macro-perspective approach.

From our retrospective analysis, we have found that the PV sector has a **dynamic feature** with rapid changes. The PV policy mechanism is very complex and thus difficult to control because of a constantly changing market dynamics.

The study found that **a good mix of supply-side policies and demand-side policies contributed to PV development**; it's proven with case studies of Germany and Japan. For example, Germany and Japan have been pioneers in the development of large deployment of PV energy based on the well-balanced mix of supply-side policies (R&D and industry) and demand-side policies (installations). Based on these policies, the country became the largest installer in the world having visible results with respect to the energy transition and economic benefits until recently.

However, faced with the fierce competition mainly driven by Chinese firms, German industry has experienced a setback provoking economic damage (job loss, trade deficits) and its market share has sharply dropped. Conversely, Japanese market was protected from the fierce global competition due to complicated institutional barriers (standards). However, Japanese PV module price stayed high compared with other countries which have open market.

Other interesting findings related to the supply-side are that **economies of scale effects** are greater than R&D impacts to reduce PV module prices. It was proven that the global module prices have been reduced mainly by Chinese export-oriented industry policy rather than other country's R&D policy (e.g. Germany). As seen, Chinese PV policy was focused on building GW large-scale plants to gain price competitiveness in the global market without investing a lot in R&D activities. The favorable industry policy in China allowed an easy access to capital to develop the PV industry. Chinese R&D efforts recently started to support the PV industry by increasing their independency of PV technology, in particular for silicon materials.

Next, since PV is not yet competitive compared to conventional energies, PV installation growth are subsidized through installation-oriented policy instruments like FIT system. The FIT system was the main driver to boost PV installations in many countries; this accompanies a rapid installation growth. Such demand-side policies are usually accompanied by supply-side policies that incite the decrease in PV costs (they are often through research or innovation within industries aiming to reduce a gradual decline in costs of demand-side policies); this was the policy objective of German FIT tariff system. However, questions were raised about the cost of the policy for FIT system and the consequence was found in the increase of **electricity tariff.**

However, Chinese PV policy strategy was quite different from that of Germany and Japan. China first focused on economic gains based on price competitiveness rather than research on technology development or energy transition through PV installations. Most of Chinese PV products were exported; they are heavily dependent on the overseas market. The country's PV strategy was recently changed to increase its technical expertise and domestic PV installations to support the domestic PV industry.

Finally, it should be highlighted the importance of the continuity of PV policy. The U.S. and France were pioneers of PV technology, but they lost their leading position because they lacked the **continuity of PV policy** (unlike Germany and Japan). South Korea lately started to enter the photovoltaic market by taking advantages of its expertise in silicon technologies; the country showed a rapid growth in both PV industry and installations. However, the rapid PV growth slowed down due to regime change (lack of the continuity of PV policy).

In conclusion, based on our retrospective analysis, two major objectives of PV policies can be defined; **the growth of PV power** and **economic development**. In addition, the **competitiveness of PV** (reduction of PV costs) is the third important variable that fundamentally appears in the background of PV policy mechanisms. In this regard, we will give a close look at those objectives in the following chapter.

Chapter 3. Criteria of policy evaluation (detailed mappings) and the application

The retrospective analysis in chapter 2 allowed us to define key variables and context associated with PV development and PV policies. We have seen how the PV sector is dynamic and constantly changing. Furthermore, we define three key policy targets of PV system from the analysis; **PV power growth**, **the competitiveness of PV** (the real cost of PV electricity in the electricity mix), and **economic gains** through PV development.

To better understand the PV policy mechanisms based on a micro point of view, it is now necessary to develop detailed mappings that explain what makes the change in the PV policy mechanisms directly or indirectly (**causal relation among variables**). In section 1, we thus construct detailed mappings according to a technological prospective method (*méthode de prospective technologique*) proposed by N. Popiolek (refer to her book in terms of the guidelines of the construction of detailed mappings). It results in three detailed mappings around each core variable of specific policy target with measurable elements that impact directly or indirectly the core variable, by identifying levers and constraints.

In section 2, three different and complementary analyses are conducted based on the proposed detailed mappings with empirical data of selected countries. The developed detailed mapping allows policymakers to conduct both ex-ante and ex-post policy evaluation if all data are available. This method also helps define which variables reduce the effectiveness of PV policy and prepare policy actions to improve the policy system. We identify problematic points giving a close look at the causal relations between variables. In this regard, we discuss about critical limits and risks of PV policy system and analyze the dynamics of each issue (section 3).

1 Criteria of policy evaluation (detailed mappings for specific policy targets)

The schematic map, which is defined in the previous chapter, gives a global overview of the PV policy mechanisms. However, as seen with case studies, the policy focus differs from one country to another under different policy context. Therefore, the aim of this chapter is to take a deeper look at individual policy objective using detailed mappings. The detailed mappings allow us to conduct an in-depth comparison of different approaches for analyzing PV policies and consequences in terms of a specific and well-defined policy objective.

As introduced, in the following sections, three detailed mappings are developed with regard to important policy targets that were identified from the previous chapter. The detailed mappings help define mutual relations between variables leading to a better understanding of specific PV policy systems.

The tool to develop detailed mappings is adapted from N. Popiolek's methodology (Popiolek, 2015), which suggests a systemic approach. She proposes a technological prospective method (*méthode de prospective technologique*) that helps develop prospective scenarios for decision makers. The method is referred to the *structural analysis*; the method aims to represent a system by using key variables to identify a specific problem. The structural analysis and the following systemic analysis can be used for future studies.

The method used in this chapter is a graphic tool that gives an overview of direct influences among key variables. The retrospective analysis (chapter 2) helps us identify key variables to build the detailed PV system. We then develop three detailed mappings around defined important policy objective; certain numbers of key variables are selected to present the systemic perspective for each objective. The method aims to organize these variables around a policy target in a dependency graph. The detailed mappings are set out to demonstrate the dependencies of variables, but exclude retroactive impacts among them. Each variable is a measurable element with a unit and it may depend on other variables and influence others.

The first step is to define the representative '***core variable*** (*variable cœur*)' of a policy target. Then, the variables that directly affect the core variable are included in the first group of influencing variables. Next, each variable of the first group is associated with all other variables that influence it and so on. The farther a variable is from the core variable, the less its influence is direct. However, an indirect influence does not necessarily imply a low influence. The out circle variables, or frontier variable, are called the **driving variables** (*variable motrice et non dépendante*).

In this section, the core variable is represented **in red**. Based on retrospective analysis in the previous chapter, three core variables related to the PV sector have been selected for three different and complementary analyses: 1) the share of PV electricity production; 2) the economic growth through PV industry development; and 3) the real costs of PV electricity to integrate in electricity system.

The measurable key variables are indicated in blue or gray color; variables that can be influenced by a national policy are **in blue** (*leviers*) and variables out of reach of domestic PV policies are shown **in gray**.

In addition, important constraints **in yellow** have been added to give a comprehensive broader point of view of mapping. Those constraints include 1) limited factors for the system, 2) non-measurable elements (subjective) that influence the system (e.g. social acceptance), and 3) fixed environment variables (e.g. climate or available surface). We have seen that external variables and constraints are significantly important in the PV policy mechanisms. Lastly, **possible policies** have been added **in pink**.

1.1 PV demand (increased PV electricity with PV installation growth)

Based on the retrospective analysis in the previous chapter, we have understood that the policy target to realize the energy transition towards a sustainable energy system is an important driving force to expand PV power in the electricity mix. However, each country's policymakers have different political focus for this target (e.g. German perspective vs. Chinese perspective[97]).

Increasing **the share of PV electricity production (%)** in the electricity mix is one of the ultimate goals of PV demand-side policies. In this section, it is considered as a **core variable** in the energy mix; it can be measured with the ratio of PV power in the national electricity mix.

The detailed mapping on **Figure 48** demonstrates important variables and their direct or indirect relations to the core variable. Variables that directly influence the core variable are domestic electricity demand (GWh) and domestic PV production (GWh). The government's energy efficiency policy or external factors such as economic growth affect the level of the national electricity demand. The domestic energy demand differs according to government's policy direction concerning energy transition or energy efficiency. The PV power production is influenced by installed capacities of PV system and PV technological performances (e.g. average PV system efficiency or average PV load factor).

The next group of variables has impacts that are more indirect on the core variable. However, they directly affect the upper group of influencing variables. Here, PV installation is influenced by PV system demand composing of different sectors (residential, commercial, industrial and utility-scale). The profitability on PV system investment (the rate of return, %) has a significant importance to define PV system demand. Furthermore, demand-side policies like RPS or positive energy buildings and environmental consciousness also affect the PV demand.

PV profitability principally depends on three elements. They are *PV investment* (the cost of PV power generation is usually represented by an estimated LCOE), *the generated revenues*, which can be priced by given tariffs by government (PV electricity purchase price) when the electricity is sent back to the network (e.g. FIT), and the *avoided electricity consumption from the grid* in case of self-consumption. The production cost of PV electricity for investors is reduced if the initial investment in PV system is subsidized. Taxes on PV usage are possible to internalize negative externalities or to include additional grid-level costs (they are shown as PV taxes; see **Figure 50** for the detailed relations). However, with low PV penetration, this is negligible.

[97] Germany attempts to reduce CO_2 emissions as well as to phase the nuclear energy out, whereas China aims to reduce pollution caused by SOx and NOx and to meet the increasing energy demand with a rapid economy growth.

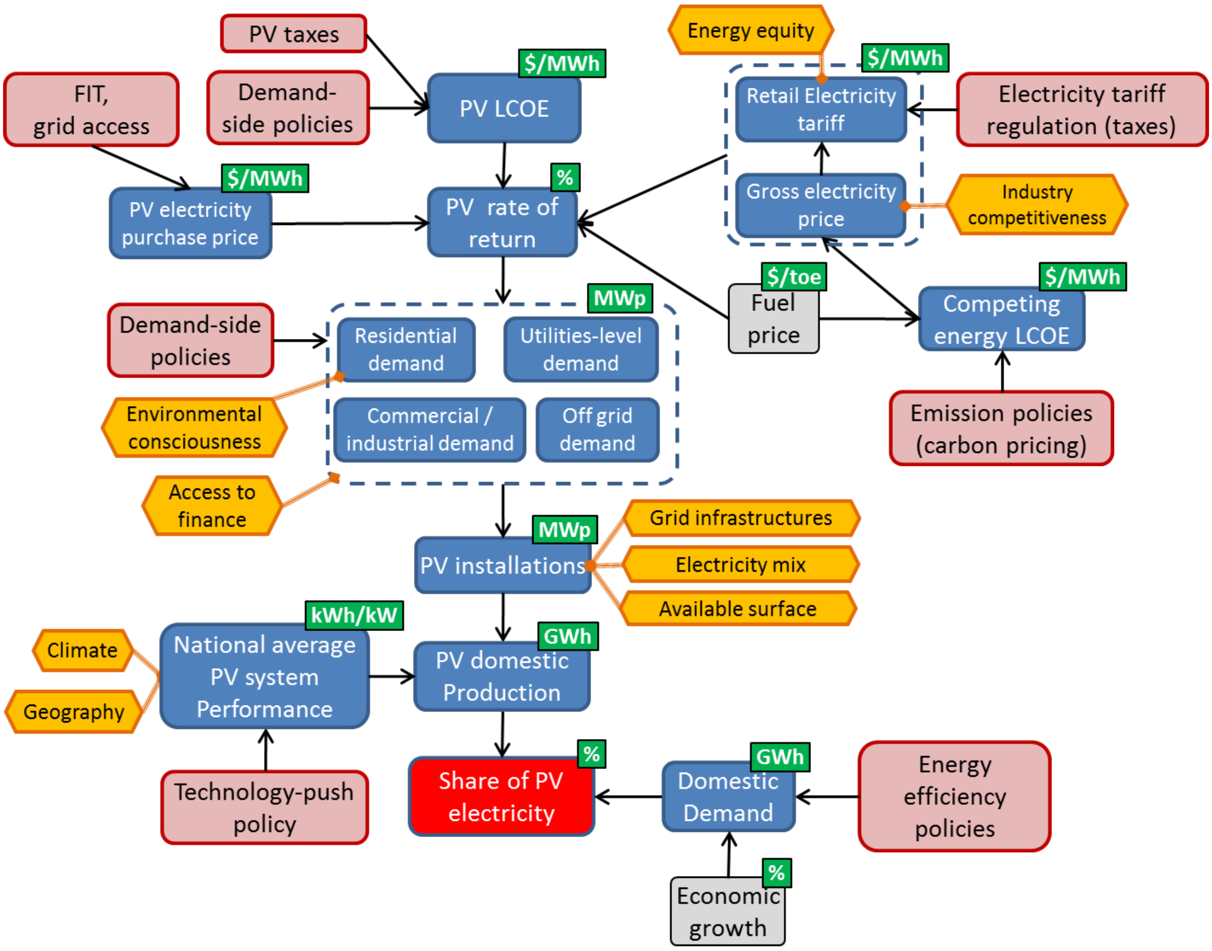


Figure 48: PV demand: the share of PV electricity in electricity mix (author's proposal)

1.2 PV supply (economic growth through PV industry development)

The economic growth by developing PV power in the present and future energy system is another important political initiative. Policymakers aim to achieve the economic growth through PV industry development. The term of green growth can be employed to explain policy maker's aspiration to gain not only the energy transition but also the economic growth by developing PV systems.

Important variables and the causality among them regarding the economic growth through PV supply are captured in **Figure 49**. The core variable is the economic growth (% of GDP or $) induced by PV industry development and the energy importation balance (e.g. avoided oil importation or increased back-up gas importation) (Difiglio, 2014). In addition, changes in electricity prices by developing PV power in the energy mix also give an impact on a country's economic growth (e.g. increased electricity tariffs for industry and household or changes in the wholesale prices of electricity)

Enhanced PV power in the energy mix provokes economic growth; the first group of influencing variables includes generated revenues from PV sector and associated industries. PV job creation also helps the economy. In addition, the avoided energy importation reduces energy dependency and increase the stability of the economy with regard to global geopolitical events. It also decreases the capital flow to foreign countries. However, the increased back-up gas to balance PV volatile output should also be considered.

PV industry revenues can be generated from domestic or overseas sales. The industry competitiveness can be measured with market shares (%). The sales are affected by the domestic production costs compared to the global prices (competitors' prices); customers would choose less expensive PV products to maximize their profits when installing PV systems. The price competitiveness can be obtained through economies of scale (e.g. China's case). In addition, there are other factors that influence the production costs; e.g., energy price, wage, capital, industrial network, or PV technology knowledge, etc.

Trade barriers can be an obstacle to export PV products in the global market. However, they sometimes establish a device to protect home market from cheap foreign products. In addition, there are other important external factors that influence PV industry growth. *Economic situation* largely affects the PV demand, which is a key variable to determine the PV sales in both domestic & global markets.

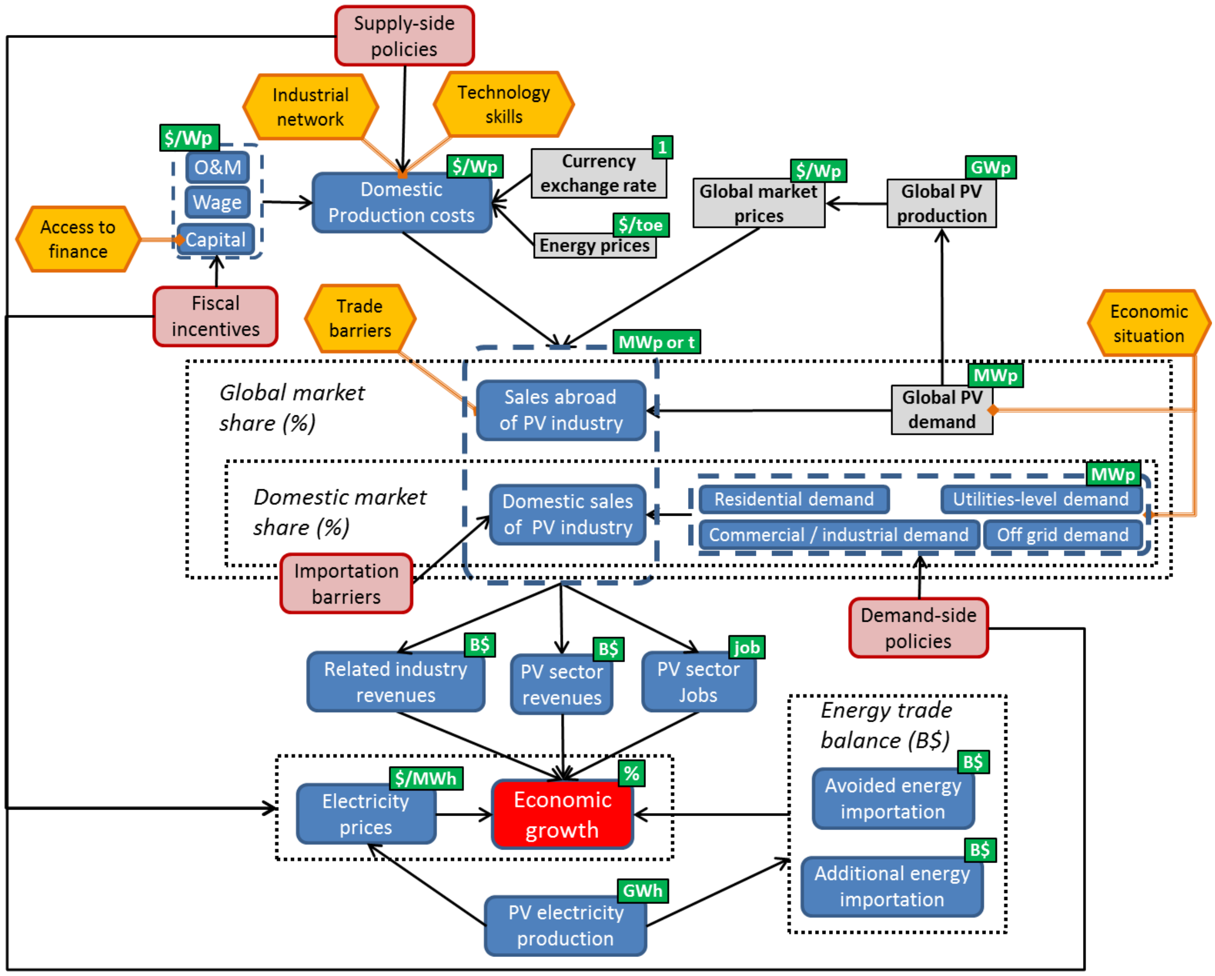


Figure 49: PV supply: economic growth through PV development (author's proposal)

1.3 PV costs (the real costs of PV power in the electricity system)

The reduction of PV costs to improve PV power competitiveness has been one of the important objectives of PV policies. However, the competitiveness of PV power in the electricity system should be evaluated in the systemic perspective. It is also important to avoid (or minimize) any negative effects on the existing electric power system. The optimal integration of PV power in electricity mix is an important policy target in developing PV systems. In this section, '**real PV electricity costs ($/MWh)**' is considered as a core variable (**Figure 50**).

The first group of influencing variables that affect the real costs of PV power includes PV power generation costs (LCOE), grid-level costs, and externalities. The second group of variables that define three segments of PV electricity is explained in the previous section (see Part I chapter 2.3).

PV power is commonly priced as levelized costs of electricity ($/kWh). Solar PV system costs are one of the important levers when defining the initial investment needed to calculate the levelized costs of PV energy (LCOE). LCOE will also depend on other factors like cost of capital, maintenance costs, lifetime, discount rate, and all costs included in the investment (e.g., system cost, financial cost, land usage cost).

Then, Grid-level costs refer to all additional costs required for grid integration into the energy system. The impact will be significant in the case of the widespread penetration of PV systems. These costs include grid reinforcement and extension. The characteristics of intermittent PV electricity also add costs related to short-term balancing and long-term adequacy while being integrated into the existing energy system (OECD/NEA, 2012; Pudjianto, et al., 2013; Ueckerdt, et al., 2013). The grid-level costs will differ according to the ratio of PV power penetration and local characteristics of grid and power supply. As seen on the detailed mapping, grid-level costs are influenced by ***electricity mix, PV intermittency and electrical network quality***.

Externalities refer positive or negative effects, which have yet to be internalized into the PV system price. They influence the national energy system and social welfare with respect to PV penetration into the energy system. There are various aspects to be considered: environmental, electricity market, technology, economic and energy position. Each country has different values according to the national energy system features and political choices.

Diverse policies can intervene to reduce the PV LCOE. For example, the government guarantees a better access to capital through fiscal incentives or public finance. In addition, soft costs can be reduced by implementing targeted policies to simplify the process (e.g. standardization) or to train people. R&D efforts will improve the PV technology performance leading to reduced PV LCOE.

Grid-level costs can be minimized by taking **optimal strategies in terms of PV integration** in energy mix by considering local condition of power supply and demand mechanisms or load factor. In order to reduce negative externalities that influence the existing electricity market, some policy options can be thought like capacity market or PV system with storage solution to reduce PV intermittency impacts on the electric power system.

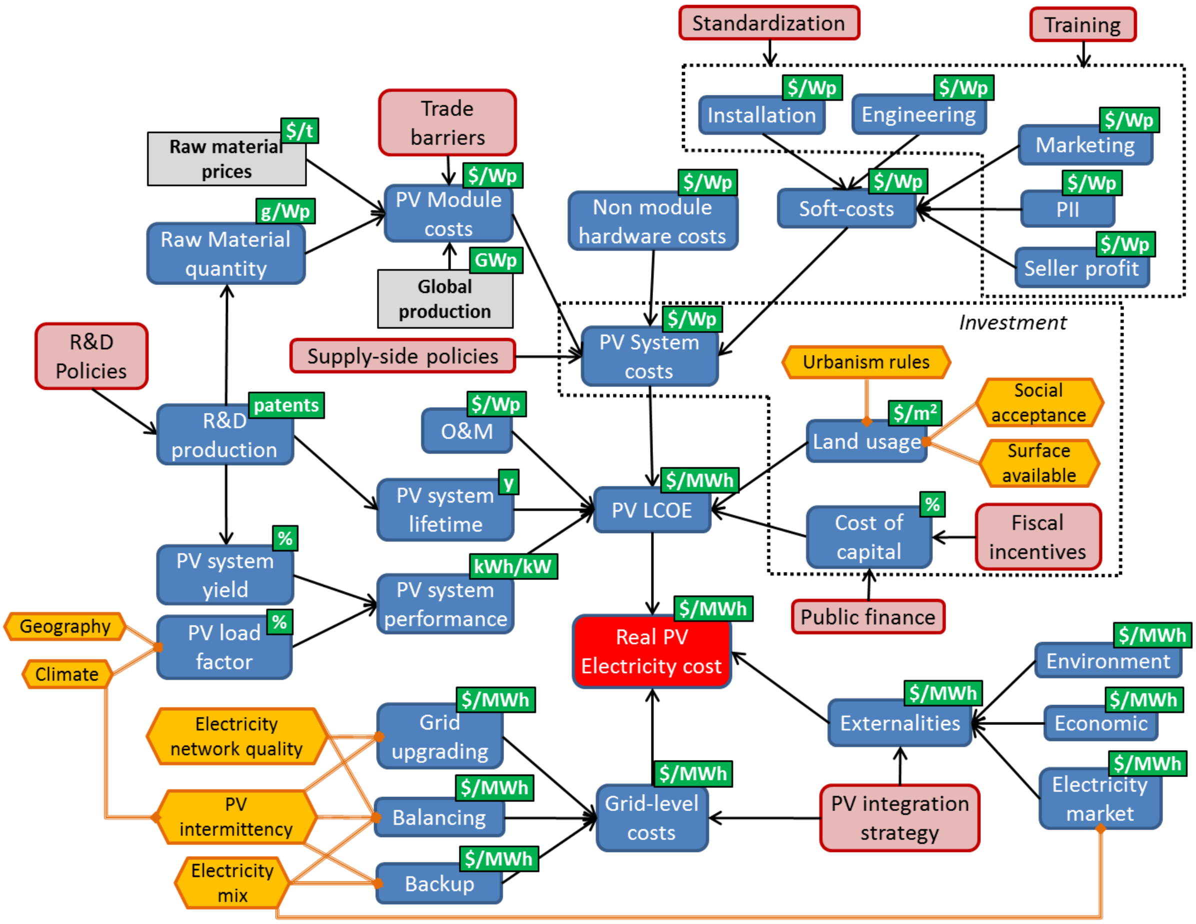


Figure 50: PV integration: reduction of real PV electricity costs ($/kW) (author's proposal)

2 Application of criteria of policy evaluation with empirical data

2.1 Comparison of three countries' PV policies: PV supply & demand

The defined detailed mapping can be used to compare the country's different approach in terms of PV supply and demand. The retrospective analysis that was conducted in the previous chapter allows us to apply the criteria of policy evaluation. In this part, three major countries (Germany, Japan, and China) in the global PV market are studied to give a comparative analysis of their different policy approach and consequences.

1) PV demand (PV installations)

The detailed mapping of PV demand on **Figure 48** defines '***the share of PV electricity in the electricity mix'*** as a core variable. The following Table LXVIII indicates the ratio of PV power in three countries' electricity mix. Germany has a notable success among three countries; more than 6% of energy demand was supplied by using PV power in 2013. It is interesting to analyze what variables have driven such difference using the detailed mapping.

The first group of influencing variable can be compared. Table LXVIII displays a significant difference between German ratio of PV power and the share in other two countries. The historical evolution of PV installations has been studied in the previous chapter. However, it is also interesting to notice that the absolute value of PV power production in China is approaching the German one despite its tenuous portion of PV power in electricity mix; this is mainly resulted from the recent increase of Chinese PV installations.

2013	Germany	Japan	China
Ratio of PV power (%)	**6.4%**	**1.4%**	**0.6 %**
Total energy demand (TWh)	525 TWh	979 TWh	4600 TWh
PV energy production (TWh)	33.4 TWh	14.3 TWh	25.6 TWh
Total PV installations in 2014	35.8 GW	13.6 GW	19.7 GW

Table LXVIII: Ratio of PV power in Germany, Japan and China (IEA PVPS, 2014)

Now, the second group of influencing variables that affect the PV domestic production can be studied; PV system performance & PV installations. The global market currently shares the similar PV technology performance thanks to the technology spillovers (de La Tour, et al., 2011). The capacity factor of three countries has small difference. However, Germany gets head in the cumulative capacity of PV installation of Japan and China. The detail mapping helps us to trace the influencing variables. PV installations are decided by the national demand in PV power and they have some constraints like grid infrastructure, electricity mix and available surface. Therefore, PV power production is mainly dependent on the installed capacity of PV system in those countries.

There are three important variables that determine PV demand; demand-side policies, environmental consciousness and PV profitability.

First, there is a difference in terms of environmental consciousness among three countries. As seen in the previous chapter, Germany (Morris & Pehn, 2015) and Japan are more willing to pay high price for energy transition towards a sustainable energy system while China put little efforts on that (the priority of Chinese energy policy was to meet the increasing energy demand caused by a rapid economic development).

In addition, the demand-side policies to promote PV power have been deployed with success in Germany and Japan over the past few decades. However, Chinese demand-side policies were much less effective until recently. Chinese PV installations have rapidly expanded in recent years driven by the strategic direction of PV policy. In conclusion, the government’s willingness to promote PV power in the electricity mix has given positive effects to stimulate the rise of PV installations.

Then, here is a question; what make the difference in PV installations between Germany and Japan? Even though Germany and Japan had similar conditions of political strategies and environmental consciousness, outputs (PV installations) in both countries were quite different. There is another important variable that determines the PV demand; **PV profitability**. It played a key role to promote the PV installations.

As seen in the chapter 2, there was a big difference of policy instrument that supported PV growth in Germany and Japan; German PV growth was mainly driven by the FIT support, while Japanese growth in PV installation was supported by subsidies.

The profitability of PV can be represented as below;

The return on investment (ROI)[98] **is** $\boldsymbol{ROI = \frac{Revenue\ on\ N\ years}{Investment} = \frac{\sum_{t=1}^{N}\frac{E_{PV}^{t}\times max(FIT,P_E)}{(1+r)^t}}{I+\sum_{t=1}^{N}\frac{O\&M^t}{(1+r)^t}-subsidies}}$

With

$\boldsymbol{E_{PV}^t}$: PV electricity produced in the year t, $\boldsymbol{r}$: discount rate,

$\mathbf{P_E}$: Electricity prices in case of self-consumption

$\boldsymbol{I}$: PV system cost, $\boldsymbol{O\&M^t}$: operations and maintenance cost in the year t.

As in the case of Germany in the 2000's, if the FIT is the only income, the ROI is as below. The PV system is profitable if the ROI is higher than 1.

$$\boldsymbol{ROI = \frac{\sum_{t=1}^{N}\frac{E_{PV}^{t}\times FIT}{(1+r)^t}}{I+\sum_{t=1}^{N}\frac{O\&M^t}{(1+r)^t}} = \frac{FIT}{LCOE}}$$

Figure 51 shows a positive correlation between the profitability of FIT system and the increase of PV installations in Germany. The FIT scheme proposed by Germany made the PV system profitable independently from the electricity prices. German FIT supports under the energy transition policy attracted investors in the PV sector, and this led to a rapid increase of PV installations in Germany.

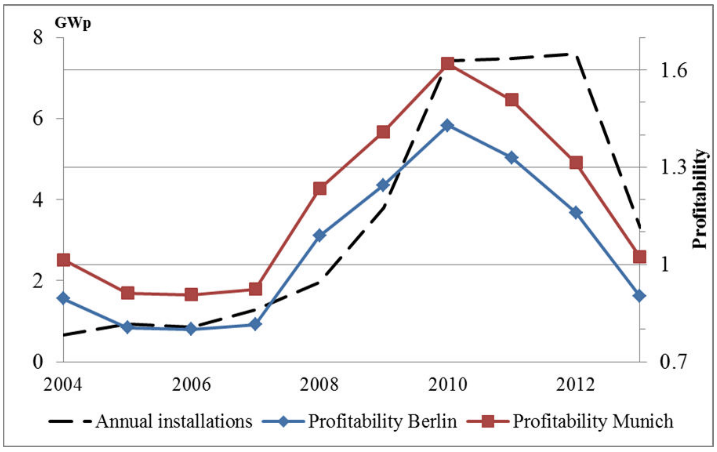


Figure 51: PV profitability of a rooftop PV system in Germany & annual PV installations[99]

However, as studied, historically, Japanese demand-side policy was mainly based on subsidy program. This reduced the initial investment of PV system installations leading to improved PV LCOE. Japanese subsidies program allowed the country to have slower but more consistent growth in PV installations

[98] (Baudry & Bonnet, 2015)

[99] Author's calculation based on data of IEA PVPS ((IEA PVPS, 2002 to 2014) and NREL PVWatt data ((NREL - PVWatts), with a PV lifetime of 20 years. After 2010, the FIT price changed during the year and the FIT is taken on January 1.

We can compare German policy to Japanese policy to stimulate PV installations. Japan has spent US$ 1.9 billion from 2000 to 2010 for subsidies of PV demand stimulation while Germany's cumulated net present value of the FIT for the same period of time is about US$ 53 billion. Over this time period, Japan installed 3.4 GWp (ratio 1.76 GWp/US$ billion) of PV systems and 41,000 jobs were created, while Germany installed 17 GWp (ratio 0.32 GWp/US$ billion) creating 133,000 jobs. The specificity of the Japanese market should be considered for the accurate comparison: e.g. high willingness to pay to protecting environment (Kimura & Suzuki, 2006), other local supports, impacts of the self-consumption and so on. However, from those data, we can see the German FIT gave more visible results of PV installation growth in a short time contributing to quickly shift to a less CO_2 emissions system but the efficiency of policy is questionable because of the high policy costs. An in-depth analysis of the FIT system is thus needed (this issue is further discussed in section 3).

Based on this perspective, it can be concluded that the active political engagement with proper economic incentives stimulates the PV installation growth, and this allows expanding PV share in the energy mix.

2) PV industry growth (supply)

The detailed mapping of PV supply helps us to analyze the economic growth through PV industry development. **Figure 49** shows that '***economic growth***' as a core value; it is measured with the ratio of improved domestic revenue performance (% or $) through PV industry growth in the GDP. Revenues are from PV industry sales, PV-related industry sales (e.g. EV, batteries) and energy importation balance. The created jobs also give positive impacts on the national economy.

	Germany			**Japan**			**China**		
	2008	**2010**	**2013**	**2008**	**2010**	**2013**	**2008**	**2010**	**2013**
PV jobs (thousand)	48	133	60	18.1	41.3	101.3	200	300	260[100]
PV domestic sales [101] (US$M)	-	28936	7932	1473	6574	13123	-	-	23220
PV export[102] (US$M $)	6314	8098	3490	6189	6446	4725	11745	25179	15759
PV sector revenues (US$M)	-	37034	11422	7662	13020	17848	-	-	38979
Contribution of PV sector to GDP (%)	-	1.1%	0.3%	0.2%	0.3%	0.4%	~0.3 %	>0.4 %	0.4%
GDP (worldbank) (US$B)	3747	3412	3730	4849	5495	4920	4558	6040	9490

Table LXIX: PV contribution to the national economy

From the Table LXIX, we can see three different aspects in terms of PV contribution to the national economy. First, German economic gains from both PV domestic sales and PV exports have been reduced since 2010. The PV contribution to the national economy has decreased from 1.1 % in 2010 to 0.3% in 2013 along with the sharp decline in PV jobs. Secondly, PV sector demonstrates a steady contribution to Japanese economy. PV domestic sales have largely increased from 2008 while its PV export has reduced over the same period. In addition, PV jobs in Japan continued to increase. Lastly, Chinese case is opposite to the German case with an outburst of PV export.

[100] (IEA PVPS China, 2013)
[101] (IEA PVPS, 2008; 2010; 2013)
[102] (UNCOMTRADE)

It can be studied to define what variables have driven those differences by using the detailed mapping of PV supply. The ***industry competitiveness*** (domestic selling price vs. competitors' prices[103]) will lead to high PV sales in both domestic and global market. The market share is a good indicator to measure it. As Table LXX shows, German market share has sharply decreased over the last years. On the other hand, China became the market leader in the global PV industry sector accounting for more than 50% of PV market share. However, Japan slightly lost its share.

	Germany			Japan			China		
	2008	2010	2013	2008	2010	2013	2008	2010	2013
PV module market share (Share of the global production %)	17%	11%	3%	8%	11%	6%	37%	50%	54%
PV module prices[104]($/Wp)	2.9-6.3	2.6-4.7	0.92	4.30	4.30	2.48	4.31	1.90	0.68
National economic growth (%)[105]	1.1%	4.1%	0.1%	-1%	4.7%	0.6%	9.6%	10.6%	7.7%

Table LXX: PV module production market share, PV module prices in the national market and economic growth

Germany had a strong PV industry. The country has put great efforts to reduce PV production costs to increase its PV industry competitiveness; German supply-side policies mainly focused on R&D (e.g. reduction of the raw material usage, optimization of the manufacturing processes) and industrial economies of scale. However, the market share is also depends on the ***competitor's prices.*** For example, Chinese players have beaten the German industry because China successfully reduced its modules prices much below the German price in the global market. It was due to lower production price base on lower energy price, low wages and an easier access to capital. The governmental support (e.g. fiscal incentives) helped lower those costs, which enabled to construct GW-scale plants in a short time. Chinese products became more price-competitive in the global market. Under open trading system, PV installers in many countries (e.g. Germany) started to use cheap Chinese products to increase their profits. As **Figure 52** illustrates, the German market selling price has sharply reduced since 2008 with the entry of cheap Chinese products.

From this case, we can conclude that the German strategy to support R&D on c-Si technologies seems to be less efficient than the Chinese political direction to gain scale effects through easy access to capital; c-Si is a mature technology with little room to cut price driven by R&D. R&D efforts on other technologies can induce better performance for that.

[103] Difficulties of access to data
[104] For Germany, both the lowest and the highest market prices are indicated (IEA PVPS, 2008; 2010; 2013). Average domestic production prices are often not available for Germany because of the relocation of domestic companies.
[105] (The World Bank(c))

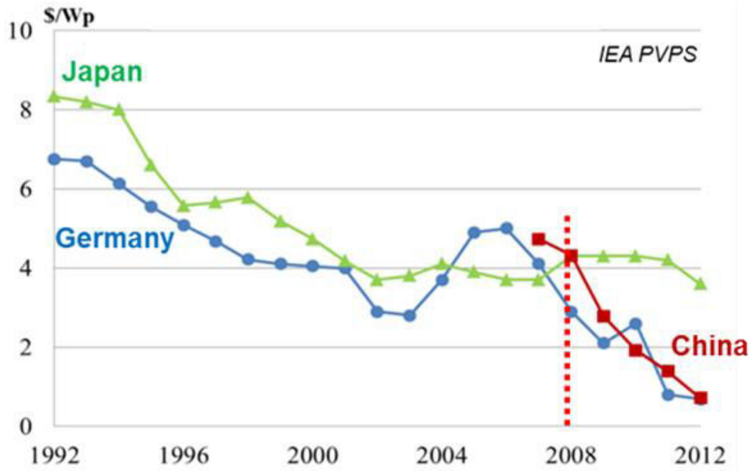


Figure 52: Evolution of PV module prices in Japan, Germany[106] and China (market prices in three countries)

The *economic situation* affects PV demand; the size of market is an important influencing factor of PV revenues. As seen in the previous chapter, Chinese local manufacturers suffered from a lack of outlets for their excessive production when the global market shrank; this will be further discussed in the next section related to PV over production issue.

In addition, the domestic PV sales can be also influenced by *trade-related policies*. For example, trade barriers can be implemented to protect the domestic market from foreign products. The example can be found with Japanese case; Japan protected its PV industry based on a standard policy. The disadvantage of this policy keeps the domestic module prices higher than other countries' prices under open market system. This leads to a higher LCOE of PV in Japan. However, Japan industry survived from the fierce price competition led by Chinese producers.

In conclusion, the competitive supply-side policies have an important role in promoting PV industry to gain a high share of market in the global PV industry.

2.2 The costs of PV electricity in electricity system

Figure 50 demonstrates detailed mechanisms to calculate the real costs of PV electricity. We have found that the real costs of PV power in the electricity mix comprise of 3 parts; PV production costs, grid-levels costs and externalities. In this section, we look at each segment based on empirical data of the defined major counties in order to understand the relations between important variables.

1) PV production costs (PV LCOE)

The PV power has evolved with accumulated experiences and knowledge over time lowering the PV LCOE. Table LXXI indicates three countries' PV LCOE with important variables that define it. As seen, solar PV system costs are key variables when defining the initial investment needed to calculate the levelized costs of PV energy (LCOE). From our retrospective study, we understood that

[106] For German market, the lowest market price was taken; this includes the entry of Chinese products in the German market (IEA PVPS, 2002 to 2013).

many countries currently share a similar PV system price except a relatively closed market (e.g. Japan) due to the globalized PV market.

	Germany (Berlin)	Japan (Tokyo)	China (Beijing)
PV module price $/Wp (2013)	0.92	2.48	0.68
PV non-module price $/kWh	0.98	0.96	0.92
PV system price (commercial) $/Wp	1.9	3.44	1.6
PV LCOE[107] $/kWh	0.19	0.27	0.12
PV system performance (kWh/kWp)[108]	900	1173	1405
Cost of capital	5%	5%	7.5%[109]

Table LXXI: PV commercial system prices and LCOE in Germany, Japan and China in 2013

As explained, the non-module prices began to occupy an important share when calculating PV electricity costs mainly for residential; they account for more than 50 % in Germany and China. In this regard, the cost reduction in soft-costs can improve the PV LCOE.

In addition, the local solar resources will affect PV LCOE; e.g. the better climate condition in China with a high load factor leads to a much less PV LCOE compared with Germany and Japan. However, the role of the cost of capital to finance PV power became more and more significant for calculating PV LCOE. The cost of capital for PV electricity varies across the globe. Germany has the lowest cost of capital in Europe (CleanTechnica, 2016): the standard assumption of 5 percent (Fraunhofer ISE, 2015b). Since Germany has a reliable condition to develop PV power supported by long-term policy direction, it is much easier to attract long-term debt investments and low-risk premiums on equity capital. The impacts of the capital cost to define PV LCOE will be much greater in the future (IEA, 2014); the difference in the cost of capital will give a larger impact on PV power production cost than the difference in solar resources (Grau, et al., 2012; Fraunhofer ISE, 2015b). This explains why Germany has a lower PV LCOE than Greece that has the higher level of irradiation.

2) Non-module costs

We now give a close a look at non-module costs since non-module sector became more important to define the PV system costs, in particular for the residential sector. In this part, the exceptional cases of two countries (France, USA) have been compared with the best-practice case (Germany) so as to better understand differences in non-module costs. Table LXXII specifically breaks down the non-module price in three countries: **Germany, France and the US**.

Germany has the lowest price for small residential PV systems compared with those in France and the US; the main differences result from non-module segments (the module price in Germany in 2012 was 1.1 $/Wp and the non-module prices stay almost constant between 2011 and 2012).

$/Wp	**Germany 2011**	**US 2012**	**France 2012**
PV System	**3**	**5.3**	**4.8**
Module	***1.82***	***1.04***	***1.21***
Non-module (total)	***1.18***	***4.23***	***3.58***

[107] Author's calculation based on minimum prices of commercial rooftop PV system (IEA PVPS trends in photovoltaic applications) and PV output estimated by PVWATTS (NREL - PVWatts).
[108] (NREL - PVWatts) with a tilt at 30°
[109] (IRENA, 2015)

Non-module hardware	0.56	0.88	0.89
Soft costs			
Engineering	0.01	0.08	0.27
Installation	0.23	0.48	0.75
PII[110]	0.03	0.2	0.44
Customer acquisition	0.06	0.37	0.53
Profit & overhead costs	0.29	2.22	0.7[111]

Table LXXII: Breakdown of the non-module prices in Germany, France and the US (ADEME, 2012; Seel, et al., 2014)

The major difference in German and the U.S. prices results from customer acquisition, grid connection costs and installations (Seel, et al., 2014). The difference in profit and overhead costs between Germany & the US is also significant.

The US has specific market features compared with Germany and France. The US market is fragmented with different PV installation environments; each state has a different policy and legal conditions which engender different PV system prices (Seel, et al., 2014; Steward, et al., 2014). Therefore, the meaning of the cumulative installation capacity can be interpreted differently to that of Germany and France.

Conversely, the German market is unified with a comparatively dense population. The US has higher customer acquisition and installation costs with longer Permission, Inspection and Interconnection (PII) process. Germany requires less time for these processes because of its unified market and practice, simplified processes and no permission fees (Seel, Op. cit.).

However, France has a similar market compared with Germany. German has largely deployed simplified rooftop building-integrated PV systems (ISB) in the residential sector; while France has promoted the installation of PV systems integrated into the building structures (IAB) through a preferential FIT scheme (IEA PVPS France, 2012). This argument is sometimes used to justify the higher cost of PV installation in France because ISB systems are usually cheaper than IABs. However, the price difference between the two systems is only 0.25 $/Wp and is due to PV racking materials (ADEME, 2012).

The cost difference between Germany and France is mainly driven by installation, engineering, PII process and customer acquisition.

The difference in the installation costs is particularly large. Installation costs are directly linked to workers' wages and the duration of the installation process. Considering the fact that wages are almost the same in France and in Germany, the longer installation times in France can explain the difference, which refers to a lack of standardization and less-qualified labor. In addition, engineering costs (mainly for system design) is probably increased because of a lack of standardization.

Customer acquisition costs refer to all activities before contract signing: e.g. marketing, advertising, site visits and negotiation. The high costs in France can be explained by a lack in the customer's preliminary knowledge or difficulties in choosing good installers (photovoltaique.info). In

[110] PII: Permission, Inspection and Interconnection
[111] Assumption based on the difference between ADEME data and IEA-PVPS data

contrast, potential customers in Germany can easily contact 3 to 5 installers in their zip code areas through lead-aggregation websites (Seel, Op. cit.).

The PII costs include grid connection costs; they amount to at least 1300$ for small residential rooftop systems in France (i.e. 0.4$/W for a 3kW residential system, the most installed residential system in France). In Germany, the PII price is 0.03$/W, which is mainly linked to the labor cost with no permission fees and no inspection process. In addition, they have a simple online declaration process for the FIT scheme via a national web-platform (Seel, Op. cit.).

In addition, the long-term policy signals are fundamentally important for the national PV development. It will give expectations about long-term market encouraging industrial investments (Nemet, 2012). Germany has a stable long-term PV policy support. However, France lacks long-term PV policy vision; the policy support of PV installation was often found in profits of installers, who looked for short-term profit margins. Accordingly, it seems that the PV policy support has not fully contributed to reducing end user PV system price in France (Observ'er, 2014). In Part III, we further discuss on this issue to propose ways to reduce PV costs in non-module sector (see Part III chapter 3).

3) Grid-level costs

Our perspective should be broadened to include grid-level costs for real economic assessment of PV electricity in electricity mix. As seen, non-dispatchable PV power requires additional costs in terms of reinforcement of power transport, short-term supply-demand balancing and back-up capacity. For the present time, however, there is no country with an enough share of PV electricity to give an obvious impact on the grid and the electricity market. Germany has the highest share of PV power (~6%) in the electricity mix. The integration costs of PV electricity would become more visible with a large penetration. This will happen soon in the future electricity mix. Therefore, it is important to give a well-defined understanding of integration costs of PV electricity as well as possible impacts on the national energy system & socio-economic features in the future. Therefore, we attempt to apply the detailed mapping based on estimated figures.

	Germany							
	Coal	Gas	Oil	Nuclear	Hydro	Biomass	PV	Other NRE
2002	52%	9%	1%	28%	4%	2%	0%	3%
2008	46%	14%	1%	24%	3%	5%	0.7%	8%
2013	46%	12%	2%	16%	3%	7%	**5.6%**	8.4%
	Japan							
	Coal	Gas	Oil	Nuclear	Hydro	Biomass	PV	Other NRE
2002	26%	25%	10%	28%	8%	2%	0%	1%
2008	28%	28%	10%	24%	7%	2%	0.2%	0.8%
2013	31%	43%	12%	0%	8%	3%	**1.4%**	1.6%
	China							
	Coal	Gas	Oil	Nuclear	Hydro	Biomass	PV	Other NRE
2002	77%	0%	3%	2%	18%	0%	0%	0%
2008	78%	1%	1%	2%	18%	0%	0%	0%
2013	74%	2%	0%	2%	18%	1%	**0.6%**	3.4%

Table LXXIII: Electricity mix change for traditional power plants in Germany, Japan and China (IEA(d))[112]

However, few studies suggest quantitative values for the total renewable energy grid-level costs. Some literatures attempt to estimate such costs with quantified data. In this study, the quantitative figures in terms of grid-level costs are quoted based on reliable studies as follows;

- Nuclear Energy and Renewables: System Effects in Low-carbon Electricity Systems[113], (OECD/NEA 2012)

- Grid Integration Cost of photovoltaic Power Generation, Direct Costs Analysis related to Grid Impacts of Photovoltaics, (Pudjianto, et al., 2013).

Each segment of grid-level costs is studied. This allows us to review the importance of grid-level costs as the level of PV penetration increases. The large penetration of renewable energies like PV and wind gives an impact on the network. The power network infrastructure should be extended or upgraded to embrace the planned deployment of renewable energies like PV power. First, at 10% PV penetration level, an OECD report estimates the grid extension and reinforcement costs ($/MWh) as Table LXXIV presents (OECD/NEA, 2012). However, the costs given by OECD/NEA seem over-estimated because they are mainly based on wind power plant studies and PV utility power plant data excluding the distributed PV system. With a good deployment strategy of distributed PV systems, the grid-level costs can be minimized. We further discuss on this issue in Part III chapter 1.

Unit: $/MWh	**Germany**	**France**	**US**	**S. Korea**
Grid reinforcement & extension	3.7	5.8	2.8	5.3

Table LXXIV: Estimation of the costs of grid reinforcement and extension at 10% PV penetration level

To give a close look at German case, **Figure 53** is shown. The first graph (left) represents the main troubles of the transportation network under Telnet management and the second graph (right) displays several planned projects of grid optimization & expansion to support the development of wind and PV until 2022 in Germany (therefore, the presented data concern both wind and PV power).

The transmission equipment has a lifetime of 40 years (Brinckerhoff, 2012) and its investment requires approximatively €400 million a year[114]. If the network is designed to allow German target of renewable electricity by 2020, which is 35% of electricity production with 210 TWh[115] (Energytransition.de), the investment amounts to around 2 €/MWh.

However, the nation-wide grid reinforcement seems mainly related to the high level of wind production because its production site is based in the northern region but demand is located in the southern regions (OECD/NEA, 2012). On the contrary, the impacts of PV production in Germany to this investment of transmission network seem very low since PV production is mainly based in southern regions near the consumption sites.

[112] Share of electricity production. Biomass includes waste. Other NRE are wind, geothermal, tide and wave. (The Shift Project Data Portal)
[113] OECD/NEA 2012
[114] The total investment amounts to €16 billion.
[115] Electricity production: 614 TWh in 2014

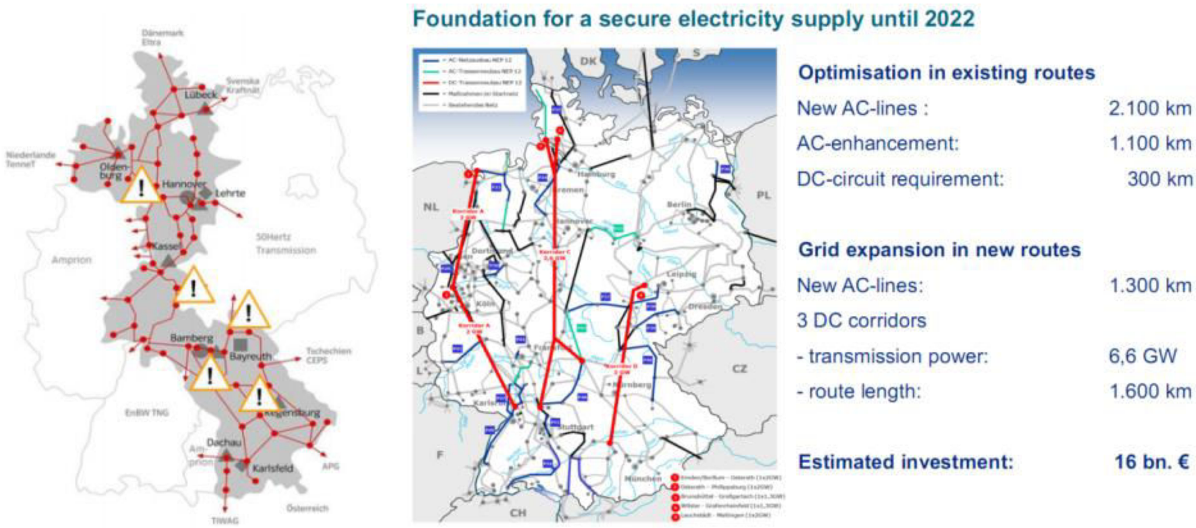


Figure 53: Detected problems on the Tennet network and network upgrading plan in Germany (Müller, 2014; TenneT, 2014)

Secondly, the **balancing costs** (short-term intermittency costs) of PV are mainly related to:

- The availability of flexible capacity in electricity mix to balance the variability of PV power
- The accuracy of weather forecast to plan the PV electricity production in the preparation of use of dispatchable capacities (adjustment of a forecast error is costly)
- The demand-supply predictability
- The size of interconnection with neighboring electric systems

Table LXXV shows **the constant increase of the redispatch frequency** since 2003 to 2013 in geographical reign of Tennet in Germany. German PV and wind energies have increased from 3.7% in 2003 to 14% in 2013 (see Table LXXIII). Furthermore, the phase-out of nuclear power from 2011 has raised the frequency significantly. The renewable energies with the variability hinder the grid management due to the uncertainty of production forecast. As seen, the action to adjust the planned production to the real demand (balancing costs) requires additional costs.

	2003	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Days	2	14	51	105	185	144	156	161	308	344	356
Redispatch actions	2	15	51	172	387	228	312	290	998	970	1009

Table LXXV : Redispatch frequency increase on Tennet network between 2003 and 2013 [116] (Tennet, 2014b)

In order to reduce the short-term balancing costs, the increased flexible capacity in the national electrical system is important. Table LXXVI shows the estimated costs ($/MWh) of short-term balancing at 10% penetration level (OECD/NEA, 2012).

Unit: $/MWh	**Germany**	**France**	**US**	**S. Korea**
Balancing	3.30	1.90	2.00	7.63

Table LXXVI: Estimation of the balancing costs at 10% PV penetration level

The relatively low costs for France & the U.S. can be explained by the availability of flexible capacity in electricity mix. Hydropower system accounts for 12.5% of French electricity mix in 2013, while only 3.2% of Germany's electricity was produced by this energy source. However, South Korea

[116] Tennet also highlights the impact of the nuclear phase out from 2011.

has a high costs for short-term balancing costs. The country has a small isolated electricity market without any international interconnection, and low hydraulic power capacities (less than 1%).

2013 : electricity production	Germany	France	US	S. Korea
Hydro power	3.2%	12.5%	6.3%	0.8%

Table LXXVII: Share of hydropower in electricity production mix (The World Bank(d))

Next, the **back-up costs** (long-term intermittency costs or adequacy) of PV electricity is an important part of the grid-level costs. They are mainly related to the **correlation between PV production and peak demand**. This correlation is measured with the capacity credit, which shows the share of the installed capacity that contributes to the peak demand of year. In this regard, the costs vary according to the geographical condition & peak demand profile; e.g., the region with a strong correlation between PV output and peak demand has low back-up costs. Below Table LXXVIII verifies this.

Unit: $/MWh	Germany	France	US	S. Korea
Back-up OECD/NEA 2012[117]	19	19	0	9
Back-up Imperial college 2013[118]	13	15		

Table LXXVIII: Estimation of the back-up costs at 10% PV penetration level

In Europe, the peak demand of electricity appears usually in the winter evening. Without storage solutions, the peak demand cannot be addressed by PV power production. This requires high cost for the long-term adequacy in Europe. In some states of the U.S., the peak demand occurs in the summer day when the sun is shining; PV has thus good capacity credit (the correlation between PV production and peak demand is very good). This gives the back-up costs nearly null.

The definition of total grid-level costs differs among studies. However we can estimate the range based on existing quantified data. Table LXXIX shows them at 10% penetration level of PV.

Unit: $/MWh	Germany	France	US	S. Korea
Maximum (OECD/NEA)	26	27	4.8	22
Minimum (Imperial College)	17	20	-	-

Table LXXIX: Estimation of the total grid-level costs at 10% PV penetration level

It is important to notice that the total grid-level costs cannot be ignored in order to largely deploy the solar PV system in the energy mix. There are some risks that the reduced LCOE can be counterbalanced by increased grid-level costs in the future energy mix. To give an idea, **Figure 54** gives an estimation of the Germany PV costs (LCOE + grid-level costs). In 2030, with 10% of PV penetration level, the PV costs of residential system can be 140 $/MWh even though PV LCOE will be reduced to 114 $/MWh[119] from 192$/MWh. It is because the grid-level costs could be increased up to 26 $/MWh in 2030.

[117] (OECD/NEA, 2012)
[118] (Pudjianto, et al., 2013)
[119] Author's calculation based on IEA's 2DS scenario.

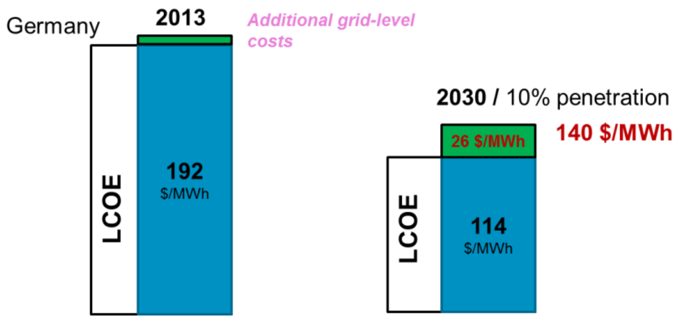


Figure 54 Estimated residential PV costs in Germany in 2030 with grid-level costs included

However, the grid level costs are very difficult to estimate without historical data, and they vary among the different studies. For example, the Imperial College study expects 17$/MWh at 10 % of PV penetration (Pudjianto, et al., 2013). Furthermore, the world energy outlook 2012 of IEA (IEA, 2012b, pp. 237-238) gives a system costs including the grid level costs ranging from around 6$/MWh to 25$/MWh (2$ to 13$/MWh for grid integration, 1$ to 7$/MWh for balancing, and 3$ to 5$/MWh for adequacy).

In this regard, proper policies to limit the grid-levels costs should be included in the future actions for promoting PV system in the future energy mix.

4) Externalities

PV electricity leads to externalities that include complex and diffuse impacts on diverse aspects of national energy system and socio-economic development. For example, some positive externalities in terms of environmental impacts (e.g. avoided emissions of GHGs) and economic development (e.g. jobs, sales, exports, etc.) are studied in the previous chapter with case studies of Germany, Japan and China. As Table LXXX shows, some studies show that the PV technology is most efficient technology to create short-term jobs (jobs per year/ MWp installed). In addition, PV is considered as one of the energy technologies with the lowest footprints of electricity generation: around 30-60 g/kWh. Even though the production of PV silicon is very energy intensive, the PV emits CO_2 much less than fossil fuels. In addition, further reduction in silicon use (e.g. thin film) will lower the carbon footprint (Parliamentary Office of Science and Technology).

Technology	**Average short-term employment factor**
(Job-years/installed MWp)	
Gas	1.0
Lignite	1.5
Coal	4.3
Wind	4.5
Hydro	5.7
Biomass	6.4
Geothermal	6.8
Solar CSP	10.2
Landfill Gas	12.5
CCS	20.5
Solar PV	21.6

Table LXXX: Average short-term employment factor by power plant (Blyth, et al., 2014)

There are also negative externalities; impacts on energy security or energy mix (see Part I chapter 2.3). However, the task to quantify all externalities of PV integration in a single unit of monetarization is seldom possible due to its complexity and diversity of impact mechanisms.

In this regard, we mainly focused on the direct externalities on the electricity system. When PV power occupies the important share of electricity mix, those impacts will challenge the national energy security. Proper policy design to minimize such impacts is necessary to ensure the security of the national energy system in relation with other power generation units. This will be further discussed in the next section.

3 Analysis of dynamics of PV systems with a focus on critical limits and risks

In section 2, we have seen negative effects and risks associated with PV policy system. In this section, we intend to conduct an in-depth analysis of the critical limits and risks of PV development in the energy mix. We decide to further investigate the following issues to understand critical problematics and dynamic mechanisms of PV system.

- Financial risks related to FIT system
- PV systemic impacts caused by the PV integration
- PV globalization impacts

The problematics can be interpreted at the national and international level. At the national level, we discuss the risks related to the sensitivity of the FIT. FIT has been the primary tool to incite the PV growth in many countries but it raised many problems. Also, this section returns to the question of systemic effects of PV integration into the electrical power system because it possesses important potential risks for PV growth as well as the national energy system. We focus on German case since it has the highest level of PV penetration in the national electricity mix. At the international level, our study focuses on the impact of PV globalization and the complexity of interactions between different national PV policies.

3.1 Limits and risks related to FIT system

3.1.1 Observed problematics related to FIT adjustment

The FIT system was implemented in many countries and it has played an important role in raising PV installations. The success of the FIT support is due to the profitability of investment. We have concluded that ***the return on investment of PV system (%, PV profitability***) is a crucial variable that influences the level of PV demand (MWp). The detailed mapping of PV installations gives an elaborated explanation for that.

These days, PV LCOE is generally higher than other competing power solutions. Over the past few decades, PV supply-side policies attempt to reduce PV LCOE by curtailing the PV system cost through improved R&D and economies of scale. At the same time, PV demand-side policies aim to stimulate the demand of PV power by providing financial support to alleviate initial PV investment or guarantee the profit margins of PV generation. The former type of support is given through subsidies to reduce PV LCOE and the latter offers higher prices than PV LCOE (e.g. FIT).

As seen, the choice of demand-side policies depends on each country's perspective. The FIT scheme played a critical role in stimulating PV installations since early 2000's mainly in European countries. The FIT system guarantees the generator of renewable electricity a certain price per kilowatt hour (kWh) at which electricity is bought. The tariff is set over a long period, commonly 20 years. This policy multiplied the volume of global installations. As seen, in contrast, Japan took PV subsidy program to reduce the initial investment of PV system and newly launched the FIT scheme.

Figure 55 displays changes in annual installations of PV in several countries since 2002 to 2014. The number of installed PV system grew very quickly in those countries that took the FIT mechanism. At the same time, PV installation peaks were observed in all of those countries.

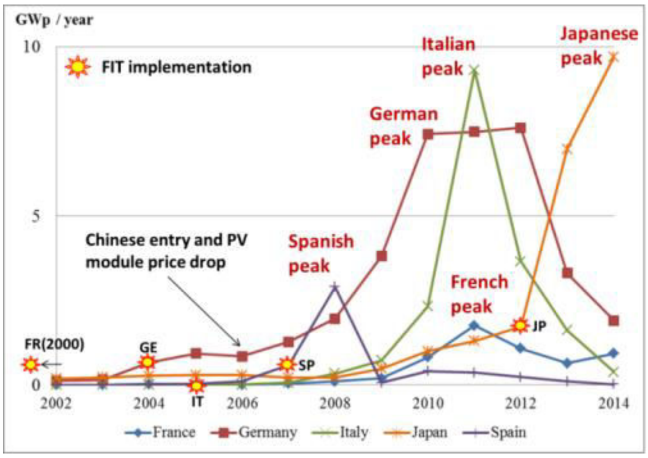


Figure 55: Annual installation peaks under the FIT system (IEA PVPS, 2002 to 2014; Campoccia, et al., 2014)

However, it is interesting to notice that Japan showed a regular growth based on subsidy program and the installation peak is a recent event after the country implemented the FIT scheme. In Japan, it was much easier for policymakers to control the profitability of PV investment with the subsidy program because the module price evolution was more predictable under its relatively closed market.

The subsidy program based on the share of PV system price enables policymakers to control the PV system price evolution. In contrast, the FIT system is production-based mechanism; policymakers only access to the data of production without having detailed information on the price of PV system purchased. Therefore, it is much more difficult to control the PV profitability. In conclusion, referring to **Figure 55**, we can see that the FIT shows the typical trends; **irregular annual installations** and **significant installation peaks**.

3.1.2 Windfall effects and increased policy costs

1) Windfall effects

The FIT scheme allows the grid access to inject generated PV power in the gird. The fixed purchase price of generated PV power based on long-term contract lowers the investment risk (removal of price risks and better estimation of actual project costs) and reduces the cost of investment.

Therefore, the PV LCOE and the sales revenue of PV electricity determine the PV profitability under the FIT mechanism. Choosing the right tariff rate is very closely connected with the success of the FIT policy; it must be set at a level that guarantees profitability for investors. If the rate is too low, there will be no or little investment. However, it should not be too high because PV power producers gain windfall profits.

As seen, the massive entry of Chinese products largely reduced the PV global module prices. This helped decline the PV LCOE in many European countries; the reduced module prices lowered PV LCOE (see **Figure 56**). Along with reduced PV module prices, the FIT mechanisms provoked **windfall profits** of PV power producers. The FIT possesses some risks:

- Overcompensation (or undercompensating) when the tariff is fixed at a higher level (or at a lower level) compared with the PV LCOE,
- Difficult adaptation of the technology cost or response lag to market changes,
- Creation of market bubbles with windfall profits and unsustainable market growth.

The characteristics are observed in many countries. There are many instances of windfall profits in the past. **Figure 56** shows yearly changes in FIT[120], module price variations and PV installations in four countries (Spain, Italy, France and Germany) from 2004 to 2013.

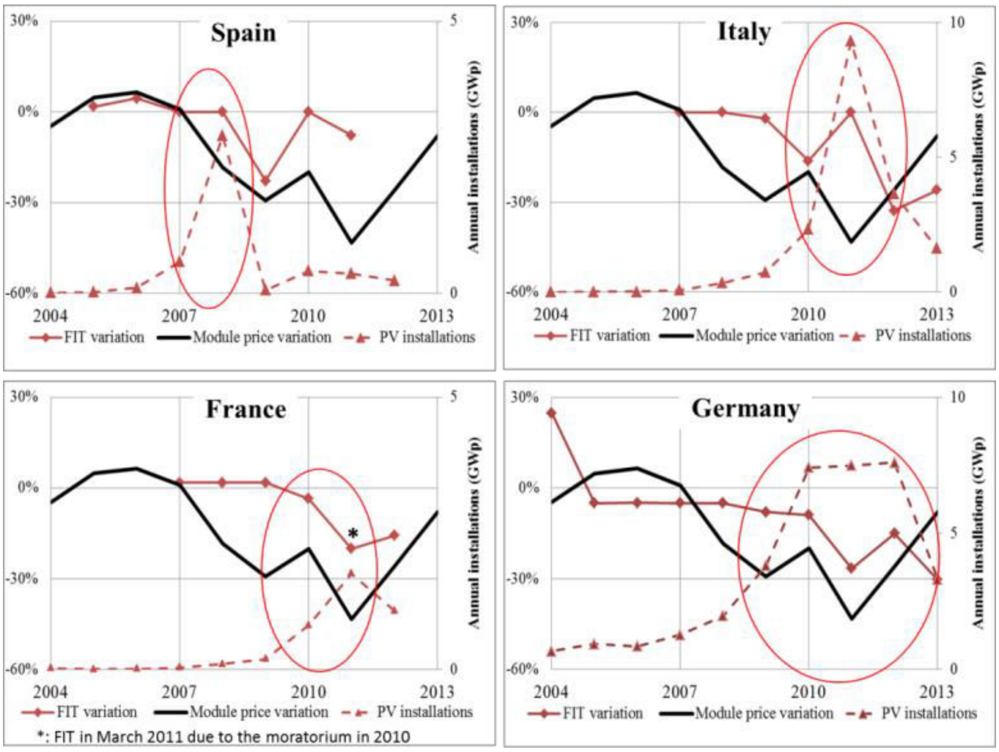


Figure 56: Comparison between the module price change and the FIT evolution compared to the previous year

The first country influenced by PV module price drop was Spain in 2008. Until 2007, the FIT tariffs were correctly set at an appropriate level, stimulating the increase of PV installations. However, in 2008, the FIT tariffs stayed at the same level even though PV module prices have fallen by about 20%. Investors have benefited from reduced PV system prices induced by the drop in PV module

[120] Residential FIT is used to show the variation of support. The support for other installation types has the similar trend.

prices. This provoked a rapid increase of PV installations (PV bubbles) (del Río & Mir-Artigues, 2014) leading to windfall profits of PV power producers. In 2009, Spain largely reduced its FIT scheme and the PV market began to be sluggish. Similar phenomena were shown in 2011 in Italy and, to a lower extent, in France. In addition, Germany went through the same process in 2009 but maintained its support policy until 2012[121].

Figure 57 gives a closer look at German case from 2009 to 2013. The graph shows that investors aimed to maximize their profits by installing PV systems just before the implementation of reduced tariffs. As PV LCOE continues to decrease, this is the moment when the PV system is the most profitable (Grau, 2014). They aim to have maximum gaps (profitability) between PV LCOE and fixed tariffs (purchase price).

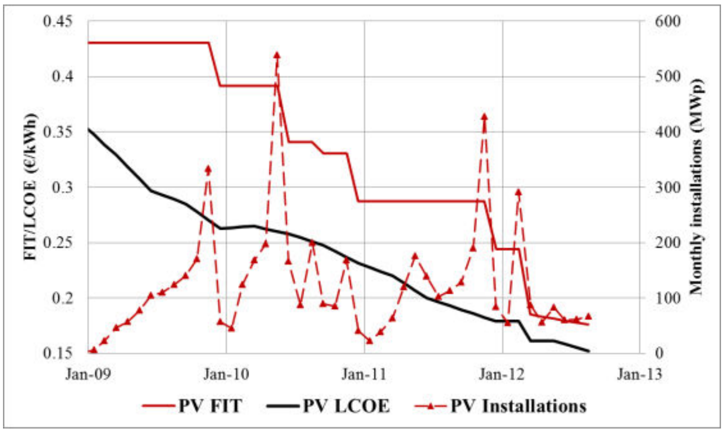


Figure 57: PV installation peaks under the FIT system in Germany for PV systems of 10 kWp – 30 kWp.

This historical analysis raises an issue in terms of the use of FIT to promote PV electricity. The FIT scheme is PV power production-based policy support. At the same time, the FIT is a very price- sensitive instrument. The difference of the rate of FIT and PV LCOE affects the profitability of investors. When the rate is too high, windfall profits follow and when it is too low, the PV market is sluggish. Based on German empirical data, we have found that the serious windfall effects were mainly caused by large-scale PV systems (**Figure 58**). We can estimate the installation peaks from utility-scale PV systems would further increase the PV development costs related to land usages and systemic costs rather than the increase from distributed PV systems.

[121] In 2012, Germany changed the FIT mechanism by taking a monthly update instead of a 6 month update. Moreover, Germany gave up the FIT support for PV installations above 10MW. (IEA PVPS, 2014).

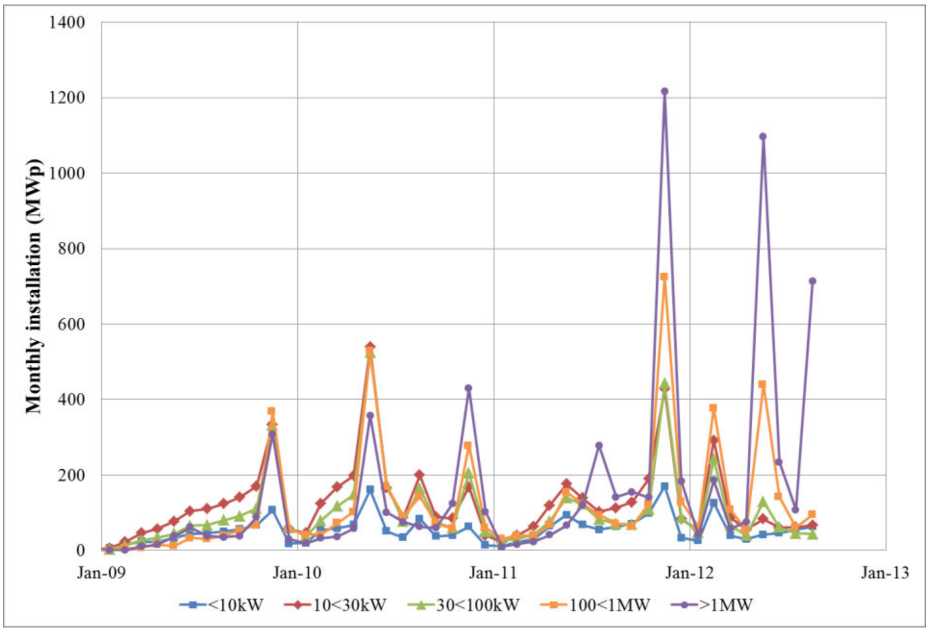


Figure 58: PV installation peaks in Germany according to the size of PV systems

In addition, the global industry movement has a greater influence on the reduction in PV module prices. Therefore, the right choice of the tariff, which reflects the dynamics of the PV industry and cost reduction of PV LCOE, is essential. Furthermore, if nationwide unique tariffs are implemented, it is possible to fail to give economic incentive to develop PV projects where they are need most (NREL, 2010).

Based on this analysis, we can conclude that FIT policy is an interesting tool to stimulate PV power generation. Well-managed FIT system is an effective policy instrument to stimulate PV deployment; it gives fair remuneration to investors. However, we have seen **the difficulty of tariff adjustment**. The FIT scheme is **very tariff-sensitive policy instrument** containing a risk factor. It is easy to control the price mechanism in a closed market. The price control system is more **complicated in an open market** because of the uncertainty of the PV module prices influenced by **fast-changing industry condition**. Therefore, the FIT scheme does **not guarantee a sustainable PV growth.**

The volatility of PV installation growth comes bigger when large-scale PV plants are included in the FIT mechanism with a nationwide tariff system (see **Figure 58**). An effective way to fix the issue related to the windfall effects of large-scale PV plants is to use **calls for tenders** under the FIT mechanism (the company, which proposes the lowest FIT, gains the contract). The large-scale PV plants will be integrated in the electricity market when they become fully competitive compared with other technologies. Therefore, **a more market-oriented support mechanism** (e.g. Feed-in-Premium) can be preferable than the FIT (Finon & Roques, 2013).

2) Policy costs of FIT and impacts on electricity prices

There is another issue regarding the FIT scheme. The FIT system placed much **financial burdens** and it was subsidized by taxpayers through household energy bills. Taxpayers (electricity end-users) mainly pay the overcompensation of renewable power production through the FIT.

Accordingly, household **electricity prices** have increased to finance the PV development and this provoked the **energy poverty** problem. End-users electricity tariffs can be influenced by **excessive remuneration** (or rapid growth of PV deployment).

Figure 59 shows German accumulated costs of FIT system (left), changes in electricity prices and in EEG (right). The FIT costs in Germany demonstrated a drastic increase over the last decade. In 2010, it grew to over € 50 billion. At the same time, Germany's household electricity rates have risen by 53% from 19.49 c€/kWh in 2007 to 29.81 c€/kWh in 2014. This is mainly due to the increased EEG (renewable energy sources act) to finance the national energy transition. German residential electricity prices are some of the highest in Europe and around 800,000 German households have difficulties to afford their energy bills (Institute for Energy Research (IER), 2013).

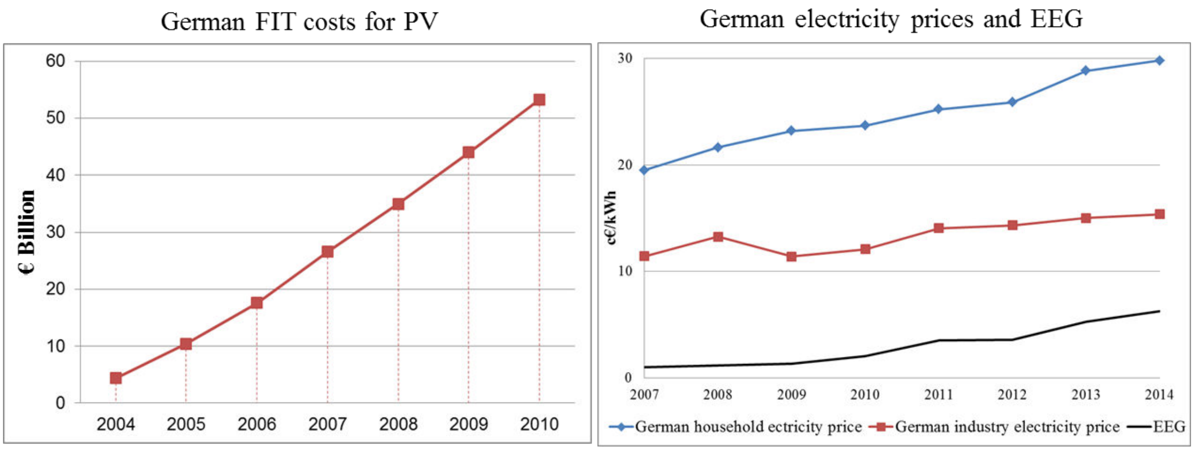


Figure 59: German accumulated costs of FIT (over 20 years) and changes in electricity prices and in EEG (Lütkenhorst & Pegels, 2014; BDEW, 2014)

We can conclude here that the FIT system does not give incentives to produce PV electricity itself as policymakers design (IEA 2014) because it is **very tariff-sensitive**. FIT is an effective instrument to promote PV installations in a short time period when it offers a profitable rate. However, when the rate became unprofitable, PV installations suddenly decrease, thus the instrument is not a sustainable system.

In addition, Feed-in-Premium (FIP) is considered as a policy instrument which better responds market price change. FIP is more market-oriented; PV power is sold based on the electricity spot market price and the generators receive a premium on top of the market price. Since the government pays only premiums, the costs will be less than FIT system. However, since it has high risks without a purchase guarantee and there is no hedge against electricity price volatility. Thus, FIP increases risks for investors compared with FIT (NREL, 2010). The PV costs under FIP system will be greater for society than under the FIT: a higher average payment per kWh with higher capital costs for the same level of PV installations.

In this regard, there is a necessity to find stable but cost-effective policy instruments for further PV growth.

Household			Industry < 2000MWh		
Year	*Electricity price (c€/kWh)*	*EEG (c€/kWh)*	*Year*	*Electricity price (c€/kWh)*	*EEG (c€/kWh)*
2000	*15.26*	*0.2*	*2000*	*7.98*	*0.2*
2007	*19.49*	*1.02*	*2007*	*12.72*	*1.02*
2014	*29.81*	*6.24*	*2014*	*20.71*	*6.24*

Table LXXXI: Electricity tariffs in Germany for household and industry (BDEW, 2014; Eurostat, 2016; 2016b; 2016c; 2016d)

3.2 Limits and risks related to systemic impacts of PV penetration in electricity system

Another important issue related to PV policies in the national context occurs in terms of PV integration in the electricity mix. In this section, it attempts to identify potential threats or limits of PV integration in the future energy mix. Possible problematics should be studied to prepare the future electricity mix. It is interesting to study German market, where the PV penetration is quite visible in the national electricity system with more than 6 % of PV power. The integration of low marginal variable energies into the energy mix in Germany brought out some impacts on the existing electrical power system. As seen, such impacts actually increase the real cost of PV electricity in the electricity mix.

3.2.1 Observed problematics related to PV integration in electricity system

1) Impacts on load duration curve

The first impact concerns the change of load duration curve with increase share of PV power. In this study, we are based on data of PV and wind production at about 16 % (solar: 5.6% + wind: 9.2%) penetration of Germany electricity mix.[122] **Figure 60** shows the yearly load duration curve (blue) and the residual load curve (red) of German electricity mix in 2014.

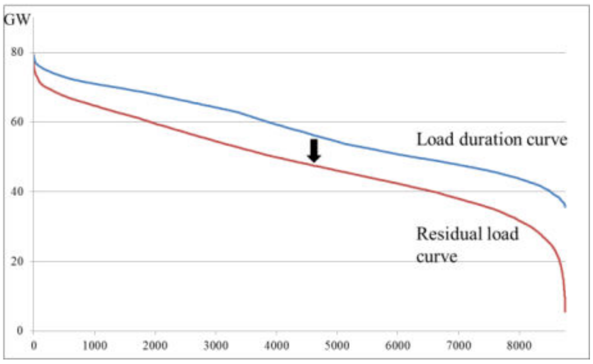


Figure 60: German load duration curve in 2014 and residual load[123]

The **Figure 60** shows a significant reduction of the residual load that is supplied by the traditional power plants. The capacity of base-load power plants that operate almost all the time during the year has been halved to 20 GW. However, the peak demand stays constant at near 80 GW; about 10 GW of peaking units are used for less than a hundred hours.

[122] No separate hourly data available for PV & wind production.
[123] Created by author with data of ENTSO-E and EEX (European Energy Exchange) (ENTSO-E; eex)

In this regard, we can conclude the integration of PV power changes the electricity mix. This implies **problems in terms of long-term investment of base-load power plants and missing money for peaking units**.

2) Over-production of PV power

Another problem is related to the over-production of electricity. **Figure 61** explains the PV over-production in Bavaria (one of landers with a high PV penetration). On April 15 in 2015, solar PV production exceeds the electricity demand, leading to over-production issue. This problem **destabilizes the electricity market equilibrium**. In case of PV overproduction, transmission system operators should market the renewable energies at power exchange even for negative prices (Fröhlich, 2014).

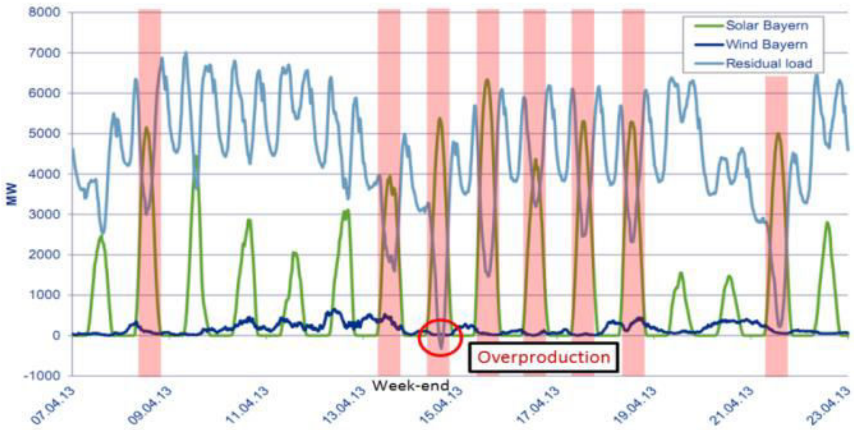


Figure 61: PV production and residual load in Bavaria (from April 7th 2013 to April 23th 2013) (TenneT, 2014)

3) Negative wholesale price of electricity

The large penetration of PV power sometimes provokes **the negative wholesale price of electricity**. Renewable energies have the priority with its low marginal cost in the electricity market; this shifts the merit order curve to the right leading to the reduction in the wholesale market price of electricity. **Figure 62** shows the constant decrease of the wholesale price of electricity (black), which is correlated with the rise of PV and wind productions (red). There are several occurrences of negative prices; for example, it was less than -200 €/MWh on December in 2012. In addition, an additional 1 GW feed-in of PV power led to an average spot price decrease of 82 c€/MWh in 2011 (Fraunhofer ISE, 2015).

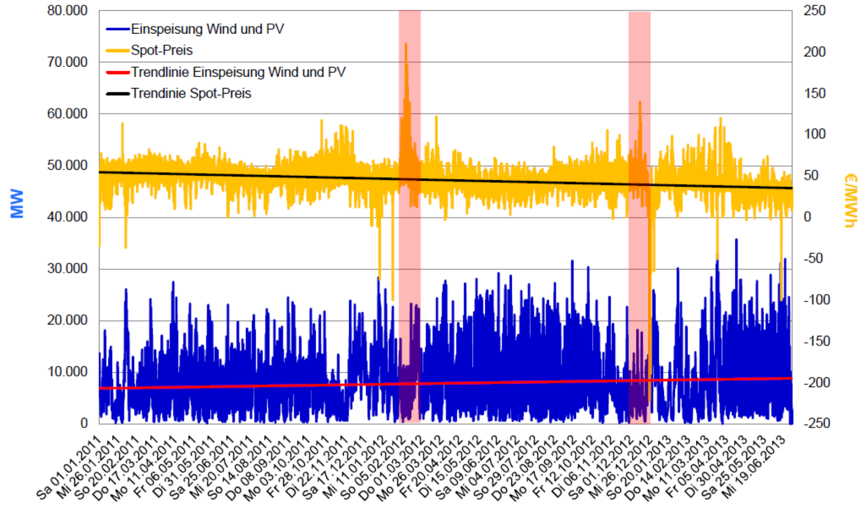


Figure 62: The decrease in average electricity price with the rise of the PV and wind productions (Tennet, Op. cit.)

4) Impacts on neighboring country's market price of electricity

With the interconnection in West Europe, the German overproduction issue has an impact on the neighbor country's market price. The situation worsens when they have an important share of electricity production using renewable energies. **Figure 63** demonstrates the wholesale price of four countries (Germany, France, Belgium and the Netherlands); there is a similar price trend among those countries. Therefore, it is important to keep in mind that a fast growth of **intermittent PV power also influences the neighboring countries' electricity market**. The PV deployment policy design should include this aspect.

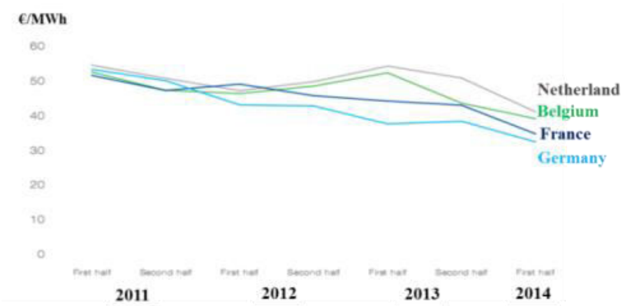


Figure 63: Decrease of the electricity market price in Germany and the neighboring countries (Tennet, 2014b)

5) Financial impacts on conventional electricity producers

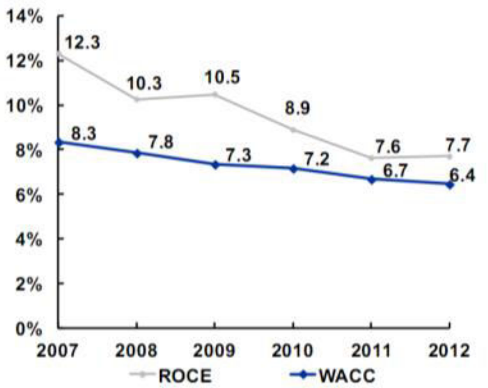
As seen, the reduction of the wholesale price of electricity gives **negative impacts on the financial situation of conventional electricity producers reducing their profit margins**. A significant reserve power supplied by conventional plants should be prepared to maintain the system balance for the integration of intermittent of PV power.

PV integration changes the marginal power plant in price-setting system. As seen, in Germany, as the share of renewable electricity rises, the margins especially of gas-fired power plants are below zero since they are hardly in operation (Schiffer, 2015; World Energy Council, 2015) Furthermore, the mid-merit power plants will become less and less profitable, which will result in decommissioning more power plants (Commissariat Général à la Stratégie et la Prospective (CGSP), 2014). This threatens the security of electricity supply.

However, the separation of PV integration impact is very difficult to conduct because of the complexity of electricity mix situation. In Germany, several important events occurred simultaneously.

- The nuclear power phase out by 2022: this induced significant changes in electricity mix.
- The volatility of the fuel price (oil, gas and coal) in recent years: this modified the investment choices and cheaper power plant between gas and coal were preferred.
- PV integration impacts on electricity mix has been compounded by the increasing penetration of other renewable sources like wind power.
- Economic situation (economic crisis reduces energy demand): this accelerates the situation that integration of renewable energies reduces the residual load that has to be served by thermal plants (CGSP,Op. cit.).

Figure 64 shows the evolution of the financial situation of the 10 largest utility producers in Europe. The left graph indicates their return on capital employed (ROCE) and weighted average cost of capital (WACC) and the right graph shows their net debt. It can be seen that their profitability has been decreased since 2007, while their net debt has increased (Roques, 2013).



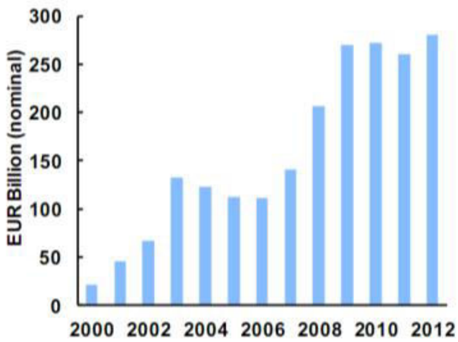


Figure 64: Financial data on the 10 largest European utilities: Return On Capital Employed (ROCE) and Weighted Average Cost of Capital (WACC) (2007-2012) (left), net debt evolution (right)

3.2.2 Systemic impacts of PV integration

1) Potential risks of PV integration in electricity mix

At low levels of PV penetration, the grid costs and the externalities are negligible. However, a number of challenges would occur with the high level of penetration of intermittent PV power in the future electricity system.

The PV integration efforts require **additional costs (integration costs)** to prepare proper infrastructures and institutions. Therefore, it is **worth reviewing the potential risks in terms of PV integration** since those issues will concern all country's PV policies. The German began to have a visible share of renewable energies including solar PV power in their electricity mix. However, it gives **hidden risks** concerning the grid system to integrate a large share of PV power; e.g. preparation of enough back-up capacity, network quality, and grid extension. In addition, with a visible share of renewable power integration, the power market started to be reshaped from a situation of electricity supply by a couple of conventional utility firms to a situation of power generation by many scattered suppliers.

In Germany, the reduced wholesale prices of electricity caused by expanded integration of renewable energies like solar PV and wind damaged the profitability of conventional utility firms (e.g. E.ON, RWE). For example, RWE decided to shut down a number of power plants (1000 megawatts by 2017) because they were no longer profitable. The company declared a net loss of €2.8 billion in financial results for 2013 (The Financial Times, 2014). The shutdown of gas and coal-fired stations could weaken the security of energy. In response to this situation, conventional firms started to take different strategic thinking to prepare the future business. E.ON decided to modify its operation based on fossil fuel and nuclear to concentrate on clean energy areas such as renewable power generation (solar and wind), power grid, energy efficiency services and smart energy metering (The Guardian, 2014; The Financial Times, 2015; www.elecreview.co.kr, 2015). However, the country needs to prepare a solid solution for long-term capacity adequacy in electricity markets.

Furthermore, German integration of intermittent energies can destabilize the electric grids possessing various technical risks (e.g. causing potential blackouts, weakening voltage or damaging industrial equipment (Institute for Energy Research (IER), 2013)) unless they have a well-designed system plan. The long-distance of transmission also provokes additional costs of grid management. As said, Germany has an important generation of renewable power (principally wind) in the northern part of the country, while the energy demand is mainly located in the southern part of the country (OECD/NEA, 2012). Furthermore, many power plants in the central and southern part of the country were closed and the power generation in the northern region became critical sources for the national energy supply. Addressing the congestion in the North-South electricity transmission network became an important issue while integrating renewable energies in Germany.

Similar problematics can be found in other countries. For example, China's PV installations grew rapidly in the recent years mainly driven by the PV policies. However, there are some challenges related to PV grid integration. Chinese PV installation plan does not include grid planning. Under the Renewable Energy Law, Chinese power network companies are required to supply grid connections for on-grid PV systems and to purchase all power produced (Huo & Zhang, 2012). However, the PV integration in the existing power system causes some technical problems like voltage fluctuation; this challenges the security of power grid system. Grid firms construct additional transmission lines and infrastructures for dispatch but other stakeholders do not support the costs. PV systems were installed in the western part of the country but the demand is relatively small, and the surplus electric power is transported to eastern region where there is high-energy demand (www.energydaily.co.kr, 2015). However, the country lacks transmission infrastructures that connect those regions; this leads to local imbalance in electricity supply and demand. Furthermore, China has insufficient technical and administration standards (codes and rules) for grid connection of solar PV systems, particularly for distributed solar PV systems.

The well-designed grid planning for PV integration in the electricity system is directly related to a reliable electricity supply. Therefore, the planning of transmission extension or dispatch infrastructure construction should be prepared under the systematic perspective with proper institutions. The costs for additional construction and operation should be shared with other stakeholders (including government). In addition, it is necessary to establish state-level solid technical and administration standards in terms of the grid-connection of solar PV systems. Otherwise, PV installations in the future electricity mix would reach the limit.

Both cases give a brief idea about potential risks of grid-level costs with visible integration of intermittent power. One obvious thing is that the large penetration of PV power will require **integration efforts with additional costs** to deal with the grid management or balancing issues. In this context, the preparation of smart solutions to address those issues is mandatory for the successful integration of PV power in the energy mix. Related institutions and system upgrading is also necessary based on open dialogues with all stakeholders.

2) Possible ways to reduce systemic costs of PV integration

Energy systems evolve with the aim of supplying energy to end-users at the lowest **integration costs**. Energy policy should aim to minimize **PV electricity costs**, while minimizing **grid integration costs** and **negative externalities** as PV penetration progresses. The PV system's integration in the current or future energy system can be justified when such efforts are based on the way of improving social welfare. Therefore, maintaining a systemic point of view is extremely important with respect to PV political choices and implementation issues. An illumination on systemic effects of PV electricity is useful to find strategies for systemic innovation with least innovation costs.

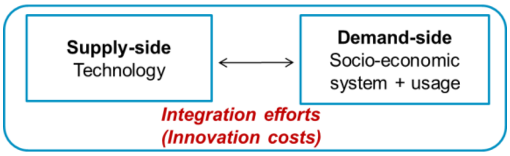


Figure 65: Integration efforts with innovation costs

Each country has different PV system economics according to the national energy system features and political choices. We have seen the additional costs of PV integration in the previous section (see section 2.2). We now discuss how to reduce them. The PV electricity costs in a society can be reduced by implementing a political mix from the following strategies:

- Minimize PV electricity costs
- Minimize grid integration costs and risks
- Maximize net benefits of externalities affecting social welfare as PV penetration progresses.

To give an example of grid-level costs, some strategical directions can be considered in order to minimize them.

Costs related to grid reinforcement and extension can be reduced by **minimizing the distance between production sites and consumers**; expansion of small decentralized systems for local consumption is a good option. For that, it is necessary to review the current structure of production and consumption to find suitable locations to install PV systems. Based on a study on local electricity supply and demand profile, a guideline for adding new capacity of PV system can be prepared by regional policy (local governments know well local specific features). It would better to target areas with local electricity production shortage or with problems related to interconnection and transport network; however, it should avoid regions that already have local over-production. This can be done in collaboration with grid operators.

Short-term balancing costs can be reduced by **improving weather forecast accuracy** or by **smoothing PV production fluctuations** (e.g. increasing geographical spread or preparing daily storage system). In addition, **demand-side management** (e.g. demand response, time-based pricing) leads to better load management. Smart-grids will be the key enabler in integrating of PV in the future system.

Next, in order to reduce costs of back-up (adequacy), the storage system should be improved. The combined PV system with energy storage system (ESS) gives further opportunities to smooth the power variation in a day; however, this requires additional costs of batteries. Policy support for R&D on this subject would help accelerate the large deployment of this system. It can be feasible by linking with other sectors like power-to-fuels storage (e.g. H_2) or vehicle-to-grid. However, when **PV electricity is consumed where the peak demand is correlated with the sun availability (good capacity credit)**, the back up costs can be minimized (e.g. California (NREL, 2001)).

3.3 Limits and risks of national PV policies with globalization

3.3.1 Observed problematics related to PV globalization

In this section, critical issues in terms of PV industry market at the international level are studied. **Figure 49** identifies the causality of key variables for economic growth through PV industry development; this mapping implies the importance of key contextual factors in the PV policy mechanisms. For example, the combined effect of the global competition with change in economic situation gives a significant influence on a country's domestic PV industry growth. Therefore, the globalization and economic condition as influencing external factors are reviewed to explain the disequilibrium of PV market (oversupply of PV products & PV industry crisis).

As seen in chapter 2, China sharply increased its production capacity over the last years and it alone accounted for around 60% of the global production capacity in 2012 (IEA PVPS, 2002 to 2013). China's entry into the PV sector was led by its export-oriented strategy with the political aids; 97.5% of the Chinese production was exported in 2006 (IEA PVPS, 2010b).

However, the PV market turned to new phase with change in economic situation. Since 2008, the global economic recession has forced many European countries to downsize their policy support (IRENA 2013). The PV market, which is not yet economically viable, was easily undermined by such political environment change. The reduced financial incentives in the European market caused by the global economic crisis reduced the global demand growth and the market slowed down; the PV market collapsed in Spain in 2009 (IEA PVPS, 2009). However, Chinese manufacturers scaled up production volumes based on GW-scale production capacity; their module production more than doubled between 2009 (4 GW) and 2010 (9 GW) (IEA PVPS, 2010).

China became the leading manufacturer producing around 10 GW of cells in 2010 (IEA PVPS, 2010). The increasing Chinese mass production combined with the decreasing demand led by the European markets resulted in a problem: **the oversupply of PV materials and equipment in a global market**. This destabilized the PV market. As shown in **Figure 66**, the market began to come up against excessive production as of 2009, leading to the inventory increase and the continuous price reduction in solar cells and modules.

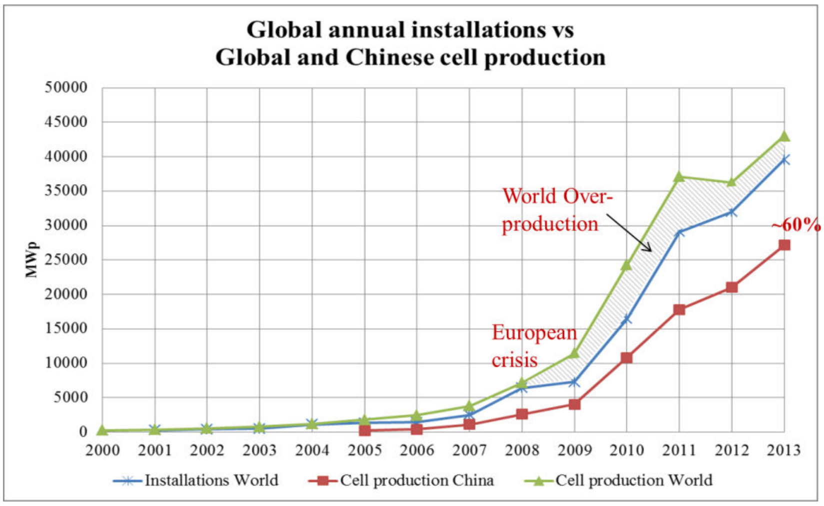


Figure 66 : Global PV supply (production) & demand (installations): overproduction

The oversupply issue provoked economic damage on both the German and Chinese side. This phenomenon hit the global PV industry sector and many firms went into the bankruptcy across the PV value chain. From 2009 to July 2012, around 40 EU producers declared insolvency and around six European producers stopped their production (e.g. Q-Cells, Schott Solar and Bosch in Germany). Furthermore, around four EU producers were taken over by Chinese investors during the period (European Commission, 2013b). At the same time, the shrinking market also caused a problem for China since its PV production was heavily dependent on overseas markets. Local manufacturers suffered from a lack of outlets for their excessive production. Chinese firms also closed down (e.g. a subsidiary of Suntech in 2012) (IEA PVPS, 2013). Through the restructuring plans after the global PV crisis, the number of companies in PV manufacturing (silicon refining through to module assembly) fell to 150 in 2013 from around 750 in 2010 (Sheppard 2013).

In conclusion, China's continuous massive production without suitable outlets for their production destabilized the global supply-demand PV system. The issue of excessive production remains to be resolved; the global PV market lost its equilibrium point. It now needs to find a new approach to arrange the unbalanced mechanisms.

3.3.2 Increased dynamics of PV policy system with globalization

The observation of the current PV market crisis allowed us to perceive the importance of external factors in a country's PV policy mechanisms. The external factor in this case is **globalization**. The PV policy mechanisms can be described as a dynamic system that evolves over time. A country's PV policy to promote economic growth through PV industry development cannot be designed and implemented in a national context. The external factors became more and more important in this era of globalization. The interaction of German PV policy with Chinese PV policy presents proofs for this.

The German FIT scheme was designed on the assumption that there was little global competition and any domestic increase in demand would be largely supplied by the German production supported by PV policies. But this was before the Chinese appeared. The German policy was set by extrapolating the drop in module prices according to observed R&D effects.

On the other hand, the Chinese PV policy mainly aimed for economic benefits without developing its local market. This influenced the implementation of the German policy to some extent because it generated new conditions that contradicted the assumptions on which the German policy was based.

When the Chinese producers sharply reduced their module prices based on economies of scale with large-scale production lines from 2008, the German module prices had to fall into line with those of the Chinese products due to PV globalization (see Table LXXXII). In 2009, the German PV system prices fell much faster than expected under the policy design, provoking uncontrolled PV installations and additional policy costs.

$/Wp	**1992**	**1997**	**2002**	**2004**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**
Germany[124]	6.8	4.7	2.9	3.7	5.0	4.1	2.9	2.1	2.6	0.8	0.7
China						4.7	4.3	2.8	1.9	1.4	0.7

Table LXXXII: Modules price changes in Germany & China (IEA PVPS)

The global market price affects the domestic sales. German installers began to use price-competitive Chinese products to increase their own profit margins, which led Germany to curtail the FIT scheme several times to adjust to such market changes. However, the adjustment was not enough to respond the market change. This leads to the German industry crisis. Germany recorded a €3.5 billion trade deficit in solar components with China during 2010 to 2012 (European Commission 2014). In addition, in Germany, only around 40 PV firms with about 11,000 employees were operation at end of 2013 compared to 2008's situation with 62 companies with more than 32 000 employees (IEA PVPS application report 2014).

This experience gives German policymakers opportunities to consider the importance of external influencing factors and the increased dynamics of PV sector in terms of PV policy design and implementation. In addition, China needs a well-balanced policy mix to achieve long-term benefits; otherwise, their industry-focused policy strategy, which heavily depends on the overseas market, is too risky to pursue. This issue will be further discussed in Part III.

[124] For German market, the lowest market price was taken; this includes the entry of Chinese products in the German market (IEA PVPS, 2002 to 2013).

4 Conclusions

The proposed detailed mappings allow us and policymakers to identify what mechanisms change the core variables, what major constraints are, and where politics can intervene to improve the system. Each variable of detailed mappings is measurable. It is thus possible to evaluate the efficiency of the policy (the ratio of inputs to outcomes) and to determine at which stage the problem occurs when the policy is inefficient. This tool also helps conduct a cross-country analysis to investigate the dynamics of PV policy system. In this regard, based on the proposed detailed mappings, we have compared different mechanisms and consequences of PV policies.

From the supply-side perspective, some questions can be raised around different approaches of PV industry policy. In our analysis, we have highlighted different policy choices to reduce production costs between Germany and China. German policy gave a focus on R&D to reduce production costs through the technology progress. Chinese policy aimed to gain industry competitiveness through economies of scale. Therefore, German PV industry policy was primarily based on the anticipated increase in PV installations and price reduction through R&D efforts. Chinese policy intended to give favorable production conditions such as easy access to capital and low energy price. This raised issues on the effectiveness of German industry policy because the country's PV industry suffered from the fierce global competition. German domestic needs were indiscriminately supplied from the national or international products (mainly Chinses products) under open market. German industry policy could have thought this variable to take the dynamics of PV policy system into account.

From the demand-side perspective, we have compared German FIT to Japanese subsidies to stimulate PV installations. From 2000 to 2010, Germany installed a total capacity of 17 GWp with installations peaks, while Japan installed 3.4 GWp of PV systems maintaining consistent growth. However, taken the allocated policy cost over this time period into account, it is difficult to say which policy is more effective (German policy's ratio 0.32 GWp/US$ billion vs. Japanese policy's ratio 0.32 GWp/US$ billion). We have seen that FIT system is a very upstream system in the PV installations mapping. The effectiveness of this policy is largely dependent on PV LCOE. But it itself is very complex to predict (see **Figure 50**). We have seen that FIT system has a limit to adapt the market dynamics. In this context, a question around the stability of the FIT system is raised. Even though it largely helped install a great amount of PV systems in many countries, it was turned out as an expensive policy instrument.

In addition, potential risks and challenges related to systemic impacts have been discussed. The impacts would be greater as the level of PV penetration in electricity system increases. The systemic dynamics should be taken into account to secure the balanced growth of PV in electricity system.

By broadening our horizons to the international market, we have highlighted the difficulties of controlling the national PV policies under the globalized market. The policy towards an international competition is different among countries. Japanese PV policy of standards helped protect the Japanese market from the international competition, but failed to increase the PV competitiveness because of high module prices. The complex interactions of different country's policy strategies combined with dynamic change of context provoked unexpected policy results and destabilized the global PV market. In this regard, in this study, we concluded that the PV policies could no longer be thought without **taking the PV globalization into account**.

Unfortunately, the evaluation proposed in this thesis is **limited because of the lack of public data**, notably concerning the amount of policy inputs. In addition, it is difficult to differentiate the results (outputs and outcomes) of PV policy from the influence of policy context change, for example nuclear exit in Germany and the drop in the price of fossil fuels. This methodology may, nevertheless, be useful for those who have more access to such data for policy evaluation. This method is also useful for policymakers to determine their indicators of assessment of policy effectiveness.

Conclusions of Part II

In this Part II, we proposed two types of mapping tools which help the implementation and monitoring of public policies. They can be employed as a common basis to communicate PV policies and consequences. A schematic map of PV policy mechanisms is a useful tool providing a macroscopic overview of PV policy mechanisms at a glance from policy objective and context to results and impacts. It also helped us to identify important variables to measure the performance of PV policies. This mapping has enabled us to conduct a comparative retrospective analysis of six countries (Germany, Japan, China, the US, France and South Korea); it highlighted the variety of public policies and the dynamic feature of the PV policy. In addition, the continuity of the PV policy over the last few decades is one of the most important factors that made Germany and Japan leading countries in the PV sector, unlike the U.S. and France. In Germany and Japan, the growth of the PV sector has led to a sharp increase in PV installations and the creation of numerous jobs until the late 2000's.

However, the global PV policy context has changed with the globalization and economic downturn since a decade ago. The European PV policy has put a focus on the energy transition and economic growth based on a balanced mix of demand-side policy and supply-side policy. In contrast, Asian countries have mainly focused on production. Economies of scale have become an important criterion to lower PV prices. The entry of China supported by the supply-side policy into the global PV market has destabilized the PV sector. Countries with FIT system faced PV installation peaks and high policy costs (mainly paid by end-users) and China experienced supply excess when the European market slowed down. The global PV market needs new outlets of the oversupply.

The retrospective analysis of six countries based on the macroscopic schematic map allowed us to select three core variables: PV power growth, economic growth through the PV development and the competitiveness of PV electricity. Around each variable, a detailed mapping was created. These detailed mappings allow us to decompose the PV mechanisms with measurable variables. These proposed mappings are very useful tools to understand the impact of PV public policies; we can also measure their efficiency and identify where the problem occurs. Based on those mappings, policies can be proposed or modified to fix the problems by referring to the causal relations between variables.

With this mapping, three critical issues related to PV policy mechanisms were raised to investigate the dynamics of PV system; 1) the effectiveness of the FIT system to stimulate demand, 2) the systemic impacts of PV integration in electricity system and 3) the influence of the PV globalization. In our study, we have identified the mechanisms behind each issue.

However, the research could have been better if we had more data on policy inputs (e.g. costs of each policy which was implemented in each country), and results (e.g. breakdown of jobs which were created in the PV sector and production costs of firms in each country). Also, there are few studies on PV systemic costs. The lack of data gave limits to this study. However, with more data, the analysis would be more solid and accurate using the proposed methodology. Therefore, our research decided to provide an in-depth insight on defined critical issues with the objective to give a zoom on the dynamics of PV system. By doing so, we can infer impacts and effectiveness of PV policy implemented.

First, the high sensitivity of the FIT in the PV policy system mechanism caused unexpected problems faced with the fast-changing market dynamics. The policy instrument of FIT system provoked uncontrolled PV installation peaks in many countries and induced high policy costs. The electricity sector is currently undergoing significant changes.

Our study also highlighted the systemic impacts of solar PV power in the energy system. The real costs of PV power should be calculated in the energy system context. Even if there are complex circumstances in the energy system (e.g. decline in the prices of raw materials and nuclear exist), the impact of intermittent renewable energy like solar PV began to appear. We have presented some problematics based on the German case where the solar PV power has the highest penetration level. By taking lessons from this case, it is thus necessary to implement strategies to reduce the systemic costs of PV in the electricity system. In Part III, we propose opportunities of deploying PV systems to minimize the systemic effects based on PV self-consumption model.

Finally, we have highlighted the necessity to include the international context for the national policy design mechanisms. The PV policy system became more complex in combined with PV globalization. The complex interactions of different country's PV policies caused unexpected policy results and broke the global PV market balance. This should be further reviewed to find new equilibriums. In Part III, we will thus further model the interaction of different policies by identifying the occurrence factor with the objective to provide solutions to the unbalanced global PV market.

In conclusion, in Part II, we have shown the complexity of PV energy supply-demand mechanisms and its dynamic change. The PV policy mechanisms should be interpreted in global points of view by taking the context change, energy system and other external factor like the economic situation or globalization into account to provide an accurate insight. In Part III, we will discuss ways to improve the PV sector based on two dimensions of national and international.

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Part III: Strategic orientations of PV public policies for PV development

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Part III. Strategic orientations of PV public policies for PV development

Introduction

In Part III, we aim to propose strategic orientations to help improve PV policy mechanisms. The attempt has two dimensions from both national and international perspectives. In Part II, we have seen the complexity of PV development mechanisms. PV financing and PV systemic impacts have been defined as major problems of PV mechanisms at the national level.

Taken the defined limits and challenges into account, in chapter 1, our study aims to propose strategic orientations for PV development with PV self-consumption model. PV self-consumption can be more stable and natural way of using PV power as PV electricity prices decrease. When the PV power becomes more competitive compared to other energies, more consumers would be willing to install PV systems for their own use to their energy bills. It profits the strong point of PV systems of being able to provide decentralized power.

We also intend to demonstrate to what extent the defined risks and limits can be addressed with PV self-consumption model. Our study thus aims to demonstrate how the use of PV power with self-consumption model can limit windfall effects and reduce policy costs compared to FIT scheme. At the same time, we also intend to analyze how PV self-consumption with targeted strategies can limit systemic costs in contrast with on-grid utility-scale PV systems. We have demonstrated that the utility-scale PV sector gave the greatest influence on windfall effects with glaring installation peaks (see Part II). Our study aims to give the rationales for prioritizing sectors (e.g. supermarkets) with the best corresponding profile between PV power output and onsite demand in the short-term period. In addition, we also analyze the economics of PV systems combined with batteries in the residential sector. The study intends to give the prospective costs of PV systems in the residential sector to help policymakers prepare future policy actions. In our study, we quantify opportunities, costs, and impacts of PV self-consumption on key stakeholders according to two time horizons (2020 and 2030).

In chapter 2, we aim to give a broader perspective on the PV policy mechanisms taken the international context (globalization) into account. We study the enhanced complexity of PV supply-demand mechanisms at the international level. The study intends to provide a precise insight into globalization effects on the national PV policy mechanisms based on the coupling case studies of Germany and China. This approach helps us to highlight the importance of external factors in the national PV policy mechanisms in an open economy. Market equilibrium change influenced by external factors is explained using the international trade theory. We also analyze the relations between Chinese strategic policy and the current PV industry crisis and long-lasting trade disputes. We aim to model the complicated strategic interactions and accompanying consequences using the strategic trade theory.

In chapter 3, we attempt to propose ways out of the global industry crisis based on the international cooperation to increase the global demand. We first study opportunities of solar PV electrification program in less-developed and developing countries with the objective to provide new outlets for the global overproduction of PV products and a solution to the global energy poverty problem based on sustainable socio-economic development model (green growth). In addition, we explain how this enlarged market contributes to the global PV competitiveness using the innovation theory (e.g. the learning curve). Next, we also examine other cooperative political actions to enhance the PV system competitiveness in non-module sector based on the learning curve effect.

Chapter 1. PV development with self-consumption model

In Part II, we have seen the complexity of the national PV development mechanisms. We concluded that FIT system has limits to guarantee a sustainable PV growth because of the difficulty of price adjustment in an open and dynamic market condition. Furthermore, another problem related to energy equity was arisen as taxpayers (electricity end-users) mainly pay the overcompensation of PV power through FIT system. The global PV market thus needs a new policy approach which is less costly and brings a sustainable growth of PV installations. At the same time, the large penetration of PV power in the electricity mix accompanies additional costs in terms of grid upgrading, balancing and backup. PV integration in the existing electric power system can affect the security of national energy system when it gives negative impacts on the profitability of conventional power plants. Strategies to address these issues at least costs are thus necessary. In this context, we aim to explore opportunities of PV development under PV self-consumption model. Our analysis aims to demonstrate how the self-consumption model will bring further PV growth with less cost than FIT and to what extend it limits the grid-level costs.

However, PV integration through a self-consumption model raises new issues related to changes in interests of stakeholders in the energy market. As explained in risk analysis in Part I, all the stakeholders should be involved in the decision-making to increase the social acceptance. Therefore, it is also important to review the point of view of stakeholders to better understand each stakeholder's position and possible threats from them.

This chapter has five sections. In section 1, we introduce the basic notion of self-consumption and characteristics before developing our case study. In section 2, a stakeholder analysis is conducted to understand stakeholders of PV integration in the electricity mix. A 2x2 Interest-Influence matrix is used to define the most influential stakeholder group towards PV integration in the electricity system. This is the important step of PV development in order to understand concerned stakeholders so as to prepare actions to any potential risks which can be created by them or strategies to draw involvement from them. Next, we conduct case studies of PV self-consumption model to look for opportunities of PV growth in the future energy system. Our approach aims to start from a sector that provides the best economic feasibility. In this regard, in section 3, we conduct a micro-economic case study to evaluate opportunities, risks, and advantages of PV self-consumption model. Supermarket surfaces in France are selected for the case study because the supermarkets have the best matching profile between the PV power output and the electricity demand. This case study also aims to analyze the effect of PV self-consumption model to what extent the identified issues are solved with this new mode of PV power use. In section 4, we extend our case study to the longer-term perspective based on residential PV systems combined with batteries. It aims to understand future attractiveness of PV systems with batteries in the residential sector. Then, we conclude this chapter with general policy recommendations (section 5).

1 Introduction of PV self-consumption model

In this section, we provide basic and theoretical understanding about the PV self-consumption model prior to presenting our case study of future opportunities of PV self-consumption. We explain the economic incentives of PV self-consumption as well as applicable areas, benefits and challenges.

1.1 Economic incentives of PV self-consumption model

PV self-consumption is a new way of using distributed PV installations in the energy system. By definition, the self-consumption of PV power refers to the use of PV electricity directly at the same site where it is produced, with a smaller amount of electricity feed into the grid (IEA, 2014). The self-consumption model reduces the distance between electricity generation and consumption through onsite consumption of power.

End-users have *economic incentives* to adapt the mode of self-consumption of PV electricity when it helps them to reduce their *electricity bills* or provide them with *some financial incentives* compared with the conventional way of purchasing electricity from the grid. In addition, when the FIT rate for residential producers is less than retail electricity prices, the self-consumption model becomes an interesting option for PV system owners. Therefore, the self-consumption of PV power is interesting for countries which have *high electricity tariffs* with *less attractive feed-in-tariffs for PV* (Matallanas, et al., 2011).

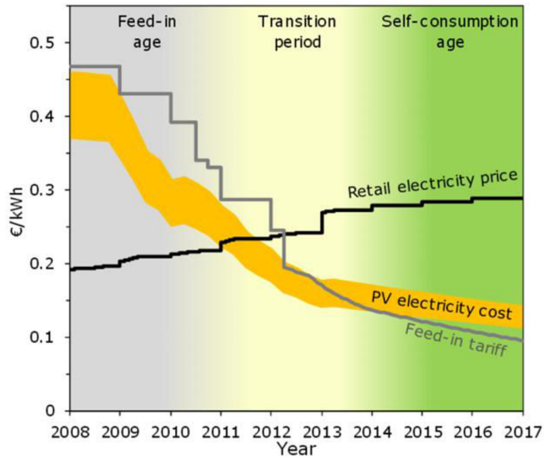


Figure 67: Transition to the ‘self-consumption age’ (Weniger, et al., 2014)

Combined with high retail rates of electricity, the reduced PV LCOE will motive end-users to install PV systems.

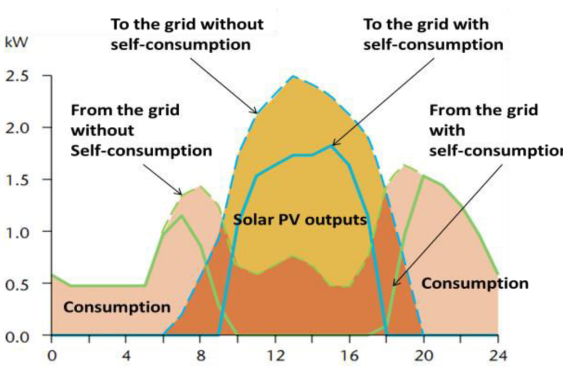
There are several factors to define the economics of PV self-consumption model. First, *PV system costs* are one of the most important variables. In addition, *the ratio of self-consumption*, which defines the rate between onsite consumption and the total production of the system installed on the site, is a very important factor in terms of deciding the economics of the self-consumed model of PV power. Therefore, it is necessary to choose PV installation sites where it is possible to best correlate the pattern of onsite energy use with PV system output to have an optimal adaptation of the load profile for the self-consumed model (IEA-RETD, 2014). However, the correlation can be improved coupled with the storage system, but it increases PV system costs.

1.2 Applicable areas

The self-consumed model can be applicable in various sectors with different ratios of self-consumption to the output of the PV system. Possible applications for each sector are described below (Ministère de l'écologie, du développement durable et de l'énergie, 2014):

1. *Industrial/commercial*: good correlation between onsite consumption & production profile with most consumption during the day
2. *Separate residential*: weak correlation between onsite consumption & production profile with impacts on the network with injected electricity. In the longer-term, residential systems can be combined with storage solution (e.g. batteries).
3. *Collective buildings*: better correlation between onsite consumption & production with broader geographical spread with interconnected collective buildings in a zone
4. *Non interconnected zone (with storage):* ideal to provide power in isolated areas to replace fossil fuels or to resolve interconnection problems.

The residential sector has a peak demand in the morning and in the evening. Therefore, it has a weak correlation between PV power output and onsite consumption and only a small share of generated PV power is self-consumed without a storage system (between 30% and 40% (EPIA, 2013)). However, supermarket and office areas have a mid-day peak which means they are more suitable for the self-consumption model without any storage system because of the correlation of the mid-day PV production and consumption pattern. The application in supermarkets shaves the peak demand during summer at midday thanks to the possibility in case of the full self-consumption. If the installed PV system cannot capture the full value of PV energy output, the return on investment will be significantly reduced. However, the correlation between PV power output and onsite consumption in the residential sector will be increased coupled with battery systems.



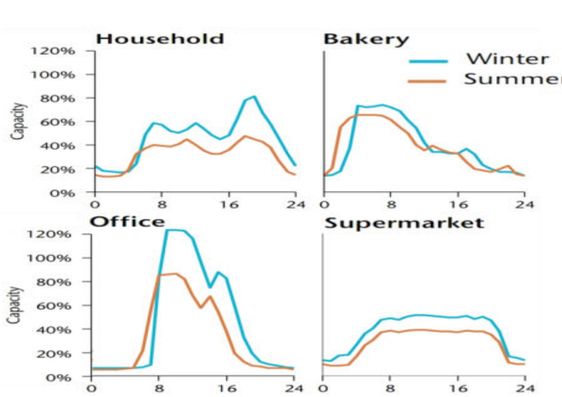


Figure 68: PV self-consumption without storage (residential PV system) (IEA, 2014; IEA, 2014b) (left)
Figure 69: Daily electricity demand and PV system outputs (IEA, 2014) (right)

1.3 Benefits of PV self-consumption model

The benefits of PV self-consumption are not limited to economic drivers of end-users. The PV self-consuming electricity model is a smart way of utilizing the nature of PV systems i.e. they are easily decentralized. With the widespread penetration of PV systems into the existing energy system, grid-related costs can be added in terms of grid reinforcement and extension (OECD/NEA, 2012; Ueckerdt, et al., 2013; Pudjianto, et al., 2013) (see Part I chapter 2.3).

The PV self-consumed system can reduce network stress. When PV power output is self-consumed during peak times, the level of avoidance is much greater by reducing power feed-in at the point of interconnection, thereby decreasing the occurrence of voltage problems (IEA PVPS, 2014b, p. 11). Under a properly designed policy framework, the self-consumption model can provide some specific benefits by minimizing distance between production and consumption to almost zero. Some benefits are captured as below (IEA-RETD, 2014);

- *Reduce power losses* during transmission and distribution (T&D)
- *Avoid system congestion*
- *Curtail investments for grid extension* when using the existing surfaces of buildings connected to the grid
- *Avoid further investment for grid upgrading* when the PV system helps reduce electricity demand peaks
- *Increase energy independence* eventually by coupling with storage systems
- *Land use.*

In addition, one important benefit of solar PV installations is related to *land use*. PV can optimize the existing infrastructures to avoid significant impact on land use; it can be easily integrated into existing buildings or parking lots.

1.4 Limits and challenges of PV self-consumption model

Limits and challenges to develop the PV self-consumed model are related to general weak points of PV system. A large penetration of distributed PV systems in the current grid infrastructures can change energy market mechanisms. Possible challenges are explained below (IEA, 2014; IEA-RETD, 2014; IEA, 2014b; EPIA, 2012):

- *Financial impact on other stakeholders (*e.g., grid operators, other utilities, end-users of electricity, government). There are concerns around the cost recovery of fixed grid costs and reduced tax revenues.
- *Difficulties for long-term planning and forecasting of the national electricity supply.* However, a well-designed cluster of small-decentralized PV systems can help smooth PV intermittency, this would enable to limit the balancing costs that can be induced by large centralized PV plants.

In addition, *new technology development* (e.g. smart grids, etc.) is very important in terms of integrating distributed PV systems into the electricity mix. The decline in storage solution price also affects the development of PV self-consumption.

It is important to understand stakeholder concerns associated with the integration of PV self-consumption model in energy system and its impact on their interests and benefits on a national level. Therefore, we conduct a stakeholder analysis in the next section.

2 Stakeholder analysis in terms of PV integration in electricity system

The introduction of the PV self-consumed model in the energy system brings about changes in stakeholder interests. As impacts can be positive or negative according to the party concerned, stakeholders will take different strategies regarding the new usage mode of PV power. Political strategies on the PV self-consumption model have a great influence on stakeholder movements. When the policy decision conflicts with their interests, they sometimes generate political pressure to affect the political decision and thereby create obstacles that hinder the use of the PV self-consumed model (IEA-RETD, Op. cit.). In this context, a deep understanding of stakeholder positions is necessary as a precedent exercise to help prepare proper steps forward to develop the PV self-consumed model. This chapter conducts a ***stakeholder analysis*** to identify the key stakeholders and their interests. The stakeholder analysis is used as the basic analytic frame when we quantify impacts from PV integration on stakeholders in section 3. Based on the defined situation of each stakeholder, possible strategies to address potential policy risks related to stakeholders can be prepared.

2.1 Identification of key stakeholders

The current energy system is comprised of several groups of stakeholders. Any group or entity whose interests may be affected or feel they have concerns with the new policy action and organizational change, can be considered in the stakeholder analysis. The stakeholder analysis used herein is frequently used in business science, but is often applied in other fields like political or environmental sciences and game theory (The World Bank(e)).

The stakeholder analysis should be conducted in a systemic way under the energy market mechanisms. Below **Figure 70** captures the key stakeholders in a simplified value chain for the energy market with the PV integration. End-users who install a PV system for their own use (self-consumption) are described as PV system owners (prosumers) interacting with other stakeholders under policy and regulations. Therefore, the new mode of PV integration is associated with stakeholder interests in the value chain for the energy market.

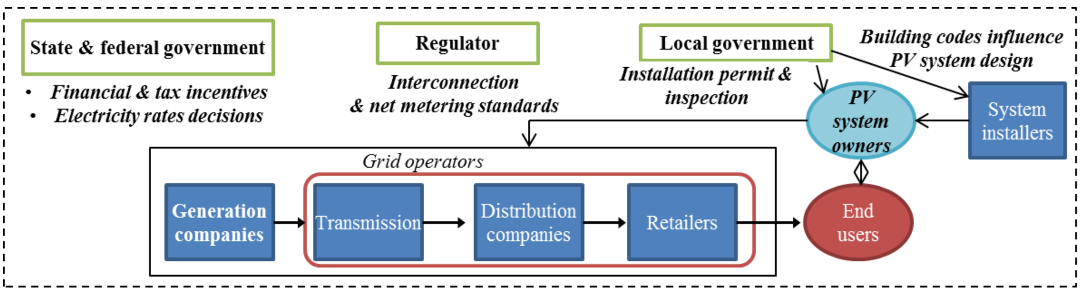


Figure 70: Stakeholders in the value chain for the energy market (NREL, 2008; European Commission, Environment Policy and Governance, 2014) (Author's production based on reference articles)

2.2 Understanding stakeholders interests and assessing the importance of influences

With the implementation of the new mode of PV power usage, stakeholders experience changes in their interests in the current energy market model. It is important to understand stakeholder viewpoints with potential opportunities or threats that they can create. In doing so, strategies can be better prepared to take into account negotiations with opposing groups (if any) or to mitigate possible policy risks from stakeholders.

Table LXXXIII gives a general explanation of the objective of stakeholders and the impacts on stakeholders' interests with the PV integration in the electricity mix. End-users who wish to install a PV system for their own use have economic drivers to adapt the new mode of power usage; they aim to either reduce their electricity bill or gain profits from the PV system installation. However, this movement will influence other stakeholder interests by changing the existing energy market mechanisms.

First, existing power generation companies and grid operators will generate less revenue; PV self-consumers buy less electricity from the grid. However, grid operators will have more activities because of an increased number of grid operations for balancing. End-users probably pay increased electricity bills because fewer consumers pay for the electricity from the grid and for the increased grid-level costs with PV integration. The government collects less tax faced with reduced electricity ratepayers and reduced sales of FIT electricity.

Furthermore, the PV integration will also affect the national energy system because the new mode of power usage provokes some issues related to grid management and balancing of power system. Compared to other centralized and dispatchable technologies such as nuclear, the grid-level costs for PV energy may be much higher (Pudjianto, et al., 2013). Even though intermittent PV energy has a low load factor compared to conventional energy sources, the network should support the maximum capacity of PV electricity that can be generated during PV production peaks or meet demand that can be requested when PV power plants are not available (OECD/NEA, 2012).

In addition, as indicated in Part I, the penetration of renewable energies sources like PV induces a sub-optimization of the current electricity mix; it reduces conventional power plant's operation hours and their load factors. At a high penetration of PV power, the load duration curve would be significantly shifted down (see Part II chapter 3). This would increase a problem in terms of future investment choice; investors would less prefer the investment, which requires high fixed costs. Solutions (e.g. capacity payments) should be prepared to address this issue to maintain the energy supply security. Also, a fair cost-sharing mechanism to finance grid management should be considered.

However, even though the large penetration of the PV self-consumed model gives rise to conflicting interests for some stakeholders, increased PV self-consumption in the energy system brings environmental (e.g. GHG emission reduction) and economic (e.g. investments in associated industry and job creation) benefits (EPIA, 2013b). Therefore, policymakers should conduct in-depth analysis to compare policy costs and expected benefits so as to find a balance among stakeholders with the objective of increasing social benefits prior to making policy choices for the national energy strategy.

Stakeholders	Objectives	Impact on stakeholder interests
PV self-consumers[125]	Pay less for electricity Profit-seeking Energy independence Preference of green electricity	Returns (positive/negative) on investment Self-consumption of PV power
Power generation companies[126]	Maximize profits Amortize existing investment	Reduced profits due to decreased sales of electricity - Reduced revenues from spot-market sales - Less investment in terms of long-term decisions
Grid operators [127] [128]	Stable supply of electricity	Grid management (e.g. balancing) with large penetration of intermittent PV power Reduced revenues due to decreased electricity consumption from the grid
End-users (electricity consumers)[128]	Pay less for electricity	Electricity rates increase with fewer ratepayers (under recovery of fixed costs) - Cost-shifting for surcharges to ratepayers - Cost-sharing of energy transition and grid upgrading
Government	Tax revenue Energy security, Energy equity, Energy transition, Green economic growth	Tax revenue loss from reduced retail sales Reduced income taxes on FIT revenues Increase energy diversification Increase economic and environmental benefits
Investors	Maximize profits	Returns (positive/negative) on investment
Associated industries	Maximize profits	Induced investments and job creation: e.g. storage, demand response, heat pumps, electric cars, companies of components of PV value chain, and smart grid

Table LXXXIII: Stakeholder analysis with penetration of PV self-consumed model

2.3 Policy risks from stakeholders

As seen, the large deployment of the PV self-consumed model conflicts with some stakeholder interests. This can be threat factors when the government decides to develop the PV self-consumed model in the energy system according as the PV system prices go down. Therefore, possible strategies to avoid expected hindrance actions from stakeholders should be considered. Targeted strategies can be used when dealing with different stakeholders. The defined stakeholders are reorganized into a 2x2 Interest-Influence matrix[129]. This is based on the World Bank's approach for stakeholder mapping in terms of policy design or reform (The World Bank(e); Bryson, 2004).

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[125] (IEA-RETD, 2014)
[126] (Haas, et al., 2013)
[127] (IEA, 2014c)
[128] (IEA, 2014)
[129] Author's analysis based on World Bank's definition

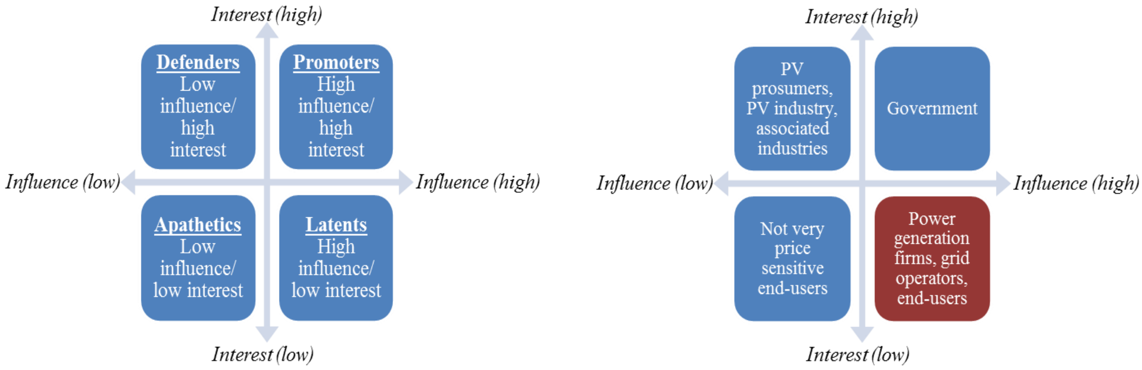


Figure 71: Interest-Influence matrix: stakeholders with the PV self-consumed model (author's analysis)

Figure 71 presents our analysis to classify stakeholders of the PV integration into 4 groups.

- ***Promoter:*** Stakeholders who have significant interests in the policy and help to make it successful (e.g. government, policy makers)
- ***Defenders:*** Stakeholders who have relative interests in the policy and make an effort to promote it in the community with the aid of media or opinion groups with little actual power (e.g. PV prosumers, PV industry, associated industries)
- ***Latents:*** Stakeholders who have no particular interest in the policy but have power to influence it when the policy impacts their interests (e.g. power generation companies, grid operators, end-users)
- ***Apathetics:*** Stakeholders who have little interest and little power; they are perhaps unaware of the policy (e.g. electricity end-users who are not very price-sensitive).

Policymakers should take into account expected change in stakeholders' interests with the new mode of energy usage. Understanding the possible influence of stakeholders on the policy decision is very important to reach the expected results (Esnault, 2014).

The position of ***promoter*** group is directly related to the success of the PV self-consumed model since promoter groups have great influence to develop it. Let us assume a government as promoter who is willing to develop the PV self-consumed model. The government prepares appropriate policy support and the institutional framework to provide favorable conditions for the PV self-consumed model's development in a national energy system. On the contrary, when the government decides against being a promoter of the new mode, the PV self-consumed model faces a great obstacle. Prior to the policy decision, the government can compare expected costs and benefits on a national level to decide on their policy vision.

Defenders are the public who want to develop the new model to gain expected interests (e.g. PV self-consumers, PV or associated industries).

The ***latent group*** should be closely examined because they represent a large potential threat. When the policy results are expected to conflict with their interests, they will strongly oppose the policy making and disturb the development of the PV self-consumed model. In this regard, targeted strategies for defined stakeholders from the latent group are needed to address any opposing movements; e.g. power generation firms, grid operators, and end-users. Therefore, in our case study in section 3, we provide quantified evidence of the loss of the latent group with PV integration based on the self-consumption model.

3 Micro-economic case study of PV self-consumption model for French supermarkets (2020)

3.1 Introduction

A micro-economic case study has been conducted to review opportunities for the PV self-consumed model by using the existing surface area of supermarkets in France. We have seen that the supermarket sector theoretically shows the best correspondence between onsite consumption and PV power output, while providing large unoccupied surface areas to install PV systems. This section describes a simulated model to give a quick yet precise idea of the opportunities of PV self-consumption. Possible challenges and risks related to externalities on stakeholders in the electricity system are also considered so as to help prepare future strategies for policymakers. The modelling methodology includes the following steps.

Firstly, the key drivers of the PV self-consumed model were studied to define the key input data; these data are related to the economics of the self-consumed system. Secondly, the production and consumption curves in supermarkets were modeled according to the input data defined in the above step. Thirdly, the collective outcomes were calculated; expected installed capacity, PV electric power output, impacts on the grid (e.g. avoided system congestion, contribution to lowering the electricity peak) and the increased energy independence. Lastly, based on the results, we aim to review costs/benefits for key stakeholders with a focus on the latent group (utility power plants, grid operators, and the government). They represent a potential threat if the PV self-consumed model conflicts with their interests. The key findings can be useful for policymakers to design PV polices related to the PV self-consumed model.

3.2 Key input data & assumptions

We have identified key economic drivers, which define the economics of the PV self-consumption system. Key data and assumptions are presented here below.

3.2.1 Electricity tariffs

Higher retail electricity prices lead to economic incentives for using a PV self-consumed system or vice-versa. In most countries, retail rates of electricity include electricity generation costs, T&D costs, profit margins and additional surcharges or taxes (IEA-RETD, 2014). Here below, we give the breakdown of French electricity tariffs because we will quantify the loss of each stakeholder caused by the PV self-consumption based on the segment of electricity tariffs.

Table LXXXIV indicates France's electricity tariff changes in residential and small industrial areas over time. France has relatively low electricity rates compared with other neighboring or European countries. However, tax represents a large fraction in the electricity tariff in France, having increasing from 25% in 2008 to 33% in 2014. Since 2009, there is a rising trend in electricity prices in both residential and industrial sectors in France.

Household			*Industry < 2000MWh*		
Year	*Electricity price (c€/kWh)*	*CSPE (c€/kWh)*	*Year*	*Electricity price (c€/kWh)*	*CSPE (c€/kWh)*
2000	*11.79*	*0*	*2000*	*6.59*	*0*
2007	*12.11*	*0.45*	*2007*	*7.01*	*0.45*
2014	*15.85*	*1.65*	*2014*	*11.57*	*1.65*

Table LXXXIV: Electricity tariffs in France (Eurostat, 2016; 2016b; 2016c; 2016d; CRE, 2014)

In the French electricity system, customers pay a fixed charge for grid connection which is set by the government (subscription fees) (Direction Générale du Trésor de la République Française, 2013)) depending on the subscribed power. In France, a time-of-use tariff option is currently applied for peak shaving; this is focused on smoothing the seasonal peak rather than the hourly variation (higher tariffs applicable from November to March). There are no taxes on self-consumed electricity in France (IEA-RETD, 2014). The government has an important role in setting electricity rates. Most supermarkets have been offered yellow tariffs[130] by EDF.

These electricity tariffs include energy costs (electricity) and the grid cost for electricity delivery (user fee for the electrical public network known as TURPE[131]). TURPE represents 90% of ERDF's revenue (ERDF). TURPE is calculated taking into account both fixed and variable costs which depend on the subscription type, the options taken, and the consumption profile. On average, yellow-tariff consumers pay a similar amount of TURPE as they do energy costs. There are other segments in the retail electricity rates; different taxes and fees are added to these tariffs (EDF(b); Enerdata, 2013; CRE, 2014; CRE, 2014b):

- **Contribution to Electricity Public Services (CSPE[132])** used to offset the charges related to public services such as renewable energy generation, social tariffs and nationwide equalization electricity tariffs. The CSPE for 2015 is set at 0.195€/kWh. In 2013, solar support represented 41% of the CSPE (Roques & Lexecon, 2014).
- **Tax on Final Electricity Consumption (TCFE[133])** is a local tax varying on the local policy. The average tax is 2.1% of the total electricity price.
- **Transmission Tariff Contribution (CTA[134])** goes towards the national electricity and gas industries fund (CNIEG) for retirement. The CTA represent 21% of the transmission part of any fixed electricity subscription. The average CTA represents 3.1% of the electricity price.
- **Value Added Tax (VAT)** is set at 20% of the electricity price. In general, yellow-tariff users are free from VAT. This tax is not considered in the study.

The diagrams in **Figure 72** show different price breakdowns of the average residential, commercial and industrial electricity rates in France in 2014.

[130] France has regulated electricity tariffs; *blue tariffs* for residential & professional segments (less than 36 kWh of electricity use), *yellow tariffs* for SMEs consumers (36-240 kWh (EDF)) and *green tariff* (more than 240 kWh) for large industrial consumers. However, yellow and green tariffs will be abolished at the end of 2015 and blue tariffs will remain until 2025 (Lévêque, 2011).
[131] French abbreviation for Tarif d'Utilisation des Réseaux Publics d'Electricité
[132] French abbreviation for Contribution au Service Public de l'Electricité
[133] French abbreviation for Taxe sur la Consommation Finale d'Electricité
[134] French abbreviation for Contribution Tarifaire d'Acheminement

In the simulation, we assumed that yellow tariffs were applicable for all the supermarkets and hypermarkets in question. In the supermarket segment, the electricity consumption per square meter (m^2) stays relatively constant regardless of the supermarket size.

A study gives a mean consumption of around ***650 kWh/m²/year*** for large supermarkets (> 1000m2) and hypermarkets (> 5000m2) (ADEME, 2008). We assumed that the consumption profile was proportional to the surface area.

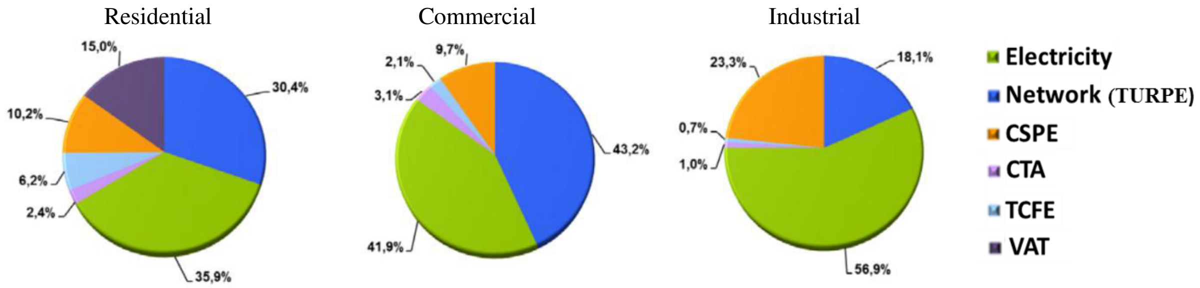


Figure 72: Price breakdowns of the average residential, commercial and industrial electricity rates in France (2014) (CRE, 2014b)

There are four different prices in the yellow tariff category: winter (November to March), summer (April to October), off-peak hours (lower price) and peak hours (higher price) for each season. Off-peak hours and peak hours vary depending on the local government policy but peak hours are usually during the day while off-peak hours are during the night (the local differences in terms of peak periods are neglected in this study). The day tariff is applicable from 6 am to 10 pm and supermarkets mainly use the day tariff. The day price during the winter is 0.09522 €/kWh and 0.04990 €/kWh in the summer (Direction de l'information légale et administrative de la République Française, 2014).Therefore, the electricity prices paid by yellow-tariff consumers are shown in Table LXXXV (tariffs used for our simulation).

€/kWh	**November to March**	**April to October**
Electricity Tariff	**0.0952**	**0.0499**
Electricity production	0.0476	0.02495
TURPE (Network)	0.0476	0.02495
CSPE	0.0195	0.0195
CTA	0.0038	0.0023
TCFE	0.0025	0.0015
Total	**0.1210**	**0.0732**

Table LXXXV: Electricity tariffs paid by yellow-tariff consumers

The use of the PV self-consumption model will bring about some changes in electricity tariffs because fewer customers buy electricity from the grid with the PV self-consumption. The changed tariff of each segment is related to stakeholder interests. The Table LXXXVI explains the possible impacts on stakeholders (losses). The possible impacts will be quantified in the next section.

Electricity production	Impact on the electricity market and revenues of the ***electricity producers***
TURPE (Network)	Reduced revenues of ***grid operators*** (transportation and distribution)
CSPE	With less consumed electricity from the grid, the CSPE paid by ***end-users*** will increase to maintain the same level. Moreover, the support of PV installation can increase the CSPE (in applicable).
CTA	***Electricity industry employees, government***
TCFE	Reduced tax revenues of ***local government***
VAT	Reduced tax revenues of ***government***

Table LXXXVI: Possible impacts on stakeholders through changes in electricity tariffs

3.2.2 PV electricity production costs

In order to calculate the LCOE[135] of the PV self-consumed model in France, we referred to the following data and assumptions.

- PV system price: 1.9 €/Wp in 2013 using c-Si PV technology[136] for large commercial roofs with simplified integration (ISB[137]), which is > 100kWp (IEA PVPS France, 2013).
- Insolation: Average global standards from 3.12 kWh/m^2/day to 4.27kWh/m^2/day (IEA-RETD, 2014). Insolation is higher in the southern regions of France. Insolation in Paris (3.32 kWh/m^2/day (INES)) was used for modeling in this study, while the location difference was ignored to simplify the simulation. If we had conducted the same study using data from the southern regions, e.g. Nice, the results would have been quite different.
- O&M: 1% of PV system price (IEA, 2010).
- A discount rate of 5% is used to consider the weighted average costs of capital (WACC) for the respective investment (Fraunhofer ISE, 2013; European Commission, 2013c).
- Module efficiency: We assumed 16% of module efficiency using the monocrystalline technology (IEA, 2014).
- 77% of PV system efficiency using electrical conversion hardware (NREL(b))
- 20 years of lifetime.

3.2.3 Available surface areas

The data on French supermarket surface areas was taken from the website, *www.distripedie.com.* The total sum of nation-wide supermarkets & hypermarkets were used; as of 2009, France had a total of about ***16 million m^2*** of supermarket (Table LXXXVII). We assumed that every supermarket was a 1-floor independent building with a flat roof usable for PV installation[138].

[135] $\mathrm{LCOE} = \dfrac{\sum_{t=1}^{n} \frac{\mathrm{Investment}_t + \mathrm{O\&M}_t + \mathrm{Fuel}_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{\mathrm{Electricity\ generation}_t}{(1+r)^t}}$

[136] **PV technology:** In this study, we considered **c-si technology**. We assumed that PV modules were installed using horizontal placement and covered the entire surface available. This is an approximation because space between modules is needed in terms of installation and maintenance. In addition, other installations can exist on roofs. Technological constraints (weights, temperature sensitiveness) were neglected. If weight matters, c-Si modules can be replaced by a thin-film solution with less efficiency (8%-10% efficiency) but cheaper selling price. This solution can be supported by a national innovation policy. The module orientation can be optimized according to the local or seasonal conditions.

[137] Simplified Building Integrated Photovoltaic Systems (Intégration Simplifiée au Bati, French standard) do not carry out the function of a construction component and may be mounted on roofs (Schuetze, 2013)

[138] The surface of supermarkets in multi-floor buildings is not considered, but the additional surface is possibly available because one-floor buildings that include supermarkets sometimes provide a larger surface than supermarket's area (e.g. buildings with shopping malls).

Total surface area of French hypermarkets *(nation-wide)*

Hypermarket (2009)	Number	Average area (m2)	Total area (m2)
E. Leclerc	467	5100	2381700
Carrefour	231	9100	2102100
Auchan	134	10500	1407000
Géant-Casino	120	7400	888000
Hyper-U	61	4900	298900
Cora	59	9600	566400
TOTAL			**7644100**

Total surface area of French supermarkets *(nation-wide)*

Big supermarket (2009)	Number	Average area (m2)	Total area (m2)
Intermarché	1494	1900	2838600
Champion-Carrefour market	987	1830	1806210
U	718	2100	1507800
Atac – Simply	414	1500	621000
Casino	380	1470	558600
Monoprix	276	1800	496800
Match	149	1550	230950
E. Leclerc	115	1800	207000
TOTAL			**8266960**

Table LXXXVII: Data on French supermarket surface areas (Distripedie, 2011; 2011b)

3.2.4 Ratio of matching between onsite consumption and PV power output

Studies explain that the ratio of correspondence between onsite consumption and PV power output is an important variable in defining the economics of the self-consumption model (IEA, 2014; 2014b; IEA-RETD, 2014).

Here below, we have attempted to justify the correspondence ratio between electricity consumption and PV power output in supermarkets using 2010 data (Swiss Confederation, Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK, Bundesamt für Energie BFE, 2010). The simulation attempts to give an approximation of opportunities for PV self-consumption. **Figure 73** demonstrates the supermarket model containing the consumption profile (winter, summer) and the maximum production curve of PV electricity.

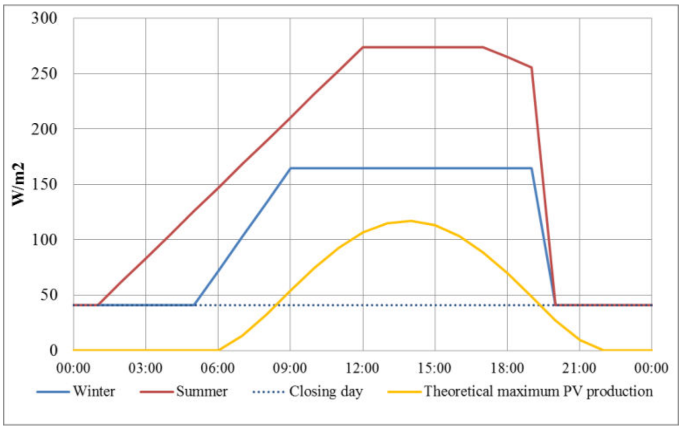


Figure 73: Consumption profile and maximum production curve of PV electricity

1) Supermarket consumption profile (winter, summer and closing day): demand

The supermarket consumption profile is based on a study, which shows an analysis of the real consumption profile (every 15 minutes) of a medium-sized supermarket (Swiss Confederation, Op. cit.). Data on real consumption profiles in winter and in summer were taken to develop the demand curve. The main sources of energy use in the supermarket sector can be divided as follows:

- Cold storage (negative cold for frozen goods and positive cold for perishable goods),
- Lighting (indoor for a large majority),
- Heating in the winter and air-conditioning in the summer.

In winter, the power demand has a linear growth from 5 am to the opening hour (9 am), it stays constant during the opening hours (~160 W/m^2) and comes back to the night demand at closure

(7 pm). In summer, the power demand has a linear growth from 1 am to midday. The peak demand period is constant between midday and 5 pm[139]. Then, the demand reduces steadily until the closing hour and comes back to the level of night demand after closure. During days-off and nights, the constant power demand is about 40 W/m^2. It is used for negative and positive cold storage (ADEME, 2008) which must operate all day constantly without interruption. The day-off level stays constant in both winter and summer.

2) Theoretical maximum PV power production: supply

The theoretical maximum PV production was determined for comparison with the above supermarket consumption (demand) curves (see **Figure 73**). The PV power production curve was developed using the European Commission's Photovoltaic Geographical Information System (PVGIS (JRC European Commission)), based on the assumption of average solar irradiation in June under a clear sky in Paris, weighted by the module's efficiency (16%) and the system's efficiency (77% (NREL(b))). We assumed that PV modules were installed using horizontal placement and covered the entire surface area available.

From the PV self-consumption model developed, we have found that:

- All the PV production can be self-consumed during the opening days,
- The PV production peak never exceeds the demand peak and there is no need for grid reinforcement.

Therefore, in this study we assumed 100% of the PV production can be self-consumed in supermarket sectors without further investment in grid reinforcement.

3.3 Results

Opportunities for the PV self-consumed model using supermarket surface areas will be defined in this part. We attempt to calculate the expected ***installed capacity, PV electric power output, impacts on the grid*** (avoided system congestion, contribution to lowering electricity demand peak), and the increased ***energy independence.*** In addition, the reduced GHG emissions and economic benefits (job creation, sales, and avoided fossil fuel imports) can be included to define benefits of the PV self-consumed model. However, these results are not quantified in this study even though there are obvious consequences. The profitability of the self-consumed model is compared under scenarios without any support and with the current FIT scheme to define policy support needed to make the model profitable. Possible quantified impacts on stakeholders are then presented with the objective of preparing strategies to mitigate policy risks from stakeholders in search of PV self-consumption growth.

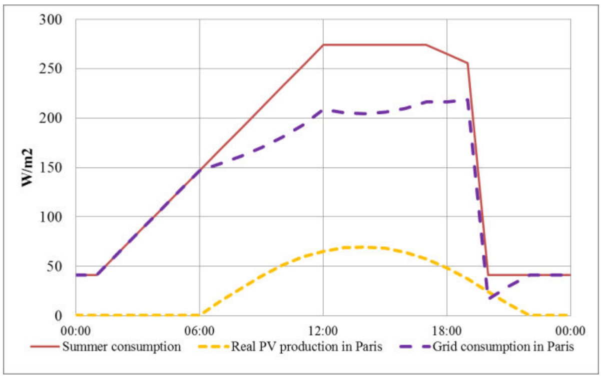
3.3.1 PV growth opportunities

The ***real maximum PV productions*** in summer and winter, which reflect the real production condition, are modeled as below. We drew the real maximum PV energy output curve, which produces less electricity than the theoretical curve. When PV power is self-consumed onsite, supermarkets use

[139] The solar midday in summer is at about 2 pm GMT in Paris

less electricity from the grid which moves the electricity demand curve down. A new shaped demand curve is expected (see **Figure 74**).

Summer



Winter

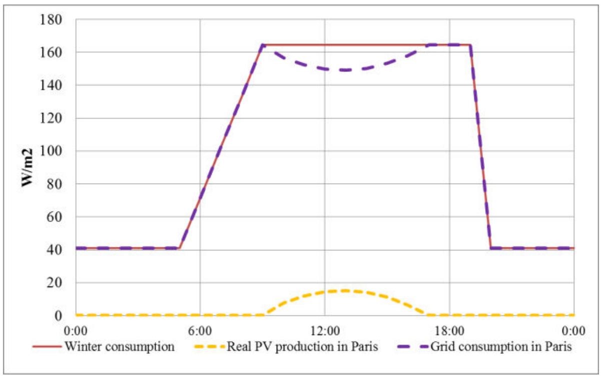


Figure 74: Demand from the grid with and without self-consumption

1) Impacts on grid

- PV production reduces the electricity consumption from the grid, thereby reducing the electricity demand peak purchased from the grid: this puts **less pressure on the grid** and **reduces the electricity transport losses.**
- The midday electricity demand peak in supermarkets is shifted to the end of the day (~ 6 pm). The impact is greater during the summer than in winter and depends on the local configuration; ***the demand peak is reduced by around 55 W/m² in Paris during the summer***. The peak shaving result will produce larger positive results in regions or countries with a midday peak in summer (e.g. the US)[140].
- Good correspondence between onsite consumption and PV power production (almost all power generated can be self-consumed[141]); therefore, **grid reinforcement is not needed**.

We can use these characteristics to look for PV deployment strategies that aim to minimize grid-level costs. 100% PV self-consumption model enables to avoid additional grid-level costs caused by PV integration without this strategic thinking. The cost related to grid reinforcement and extension of PV is estimated at 5.8 $/MWh at 10% PV penetration in France (see Part II chapter 3). Therefore, the proposed 100% self-consumption model can reduce systemic costs by up to around 22% at 10% PV penetration compared other deployment models (e.g. utility–scale PV systems). Furthermore, if we suppose these PV self-consumption systems provides a broader geographical spread in a zone, this will give better local correlation and thus reduce the balancing costs by smoothing the average PV production in the zone. This means the grid-level costs related to balancing (1.9 $/MWh at 10% PV penetration) can be also reduced.

[140] This effect is difficult to quantify because of the lack of data on the grid management costs.
[141] Assumption: when the entire available surface area is used to produce electricity

2) *PV installations*

We have also found that possible nationwide PV installations in France could represent **2.56 GWp**[142] on the condition that all the existing supermarkets in question install the PV systems on their roofs. This accounts for 47% of the total French PV installation of 2015 (Observ'er, 2015). In addition, these PV growth opportunities **enable to achieve the French solar PV installation target (8 GW by 2020)** (Legifrance.gouv.fr, 2015)**;** French cumulative installed PV capacity was 5.6 GW at the end of 2014 (IEA PVPS France, 2014).

3) *PV power output & increased energy independence*

The PV production per square meter (m^2) in Paris is given in Table LXXXVIII.

Paris	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
Monthly irradiation kWh/m^2	27.3	45.1	96.7	137.4	160.9	173.4	176.7	149.1	110.1	65.7	32.4	24.1	
PV production kWh/m^2	3.4	5.6	11.9	16.9	19.8	21.4	21.8	18.4	13.6	8.1	4.0	3.0	148

Table LXXXVIII: PV production in Paris (JRC European Commission)

The total annual PV production in Paris is 148 kWh/m^2, which is around 23% of supermarket consumption (~650 kWh/m^2/year). This means the model contributed to increase ***the energy independence*** of supermarkets to 23%. If we assume that production in Paris is representative of the French average production, the total possible production could reach 2.36 TWh[143] (0.5% of the total French electricity consumption, 447 TWh (Eurostat)).

From this simulation, we were therefore able to conclude that the supermarket sector fits well with 100% PV self-consumption mode. Furthermore, it gives opportunities to utilize the existing large surface areas to install PV modules on the roof (no additional costs or constraints related to land usages).

3.3.2 *Profitability from the viewpoint of PV system users (prosumers)*

We now want to define if the proposed PV self-consumption model is currently profitable in France. Therefore, here below, we calculate the rate of return on the investment from prosumer's perspective.

The profitability of the PV self-consumed model is country-specific depending on various factors such as the economics of PV power, electricity tariffs and political decisions. If it is not economically competitive on its own, policy support can lead PV installation growth using the defined self-consume model or vice versa. If the PV LCOE is much higher than the electricity price paid by the commercial consumers, there are insufficient economic incentives to install PV self-consumed systems in supermarkets unless they generate other financial returns on the initial investment through policy support or other revenue creation.

[142] 16 million m^2 x 160 Wp/m^2 = **2.56 GWp** (47% of the current installations)
[143] 16 million m^2 x 148 kWh/m^2/year = **2.36 TWh/year** (0.5% of the total electricity consumption of 447 TWh (Eurostat)) The solar irradiation in Paris has been used to represent the average solar irradiation conditions in France.

It is therefore important to define the break-even point of the proposed model. In order to define profitability, it is necessary to know ***the costs required*** (hereafter investment) and the ***expected revenue stream*** under the PV self-consumed model.

1) Costs to install PV systems with operation and maintenance (O&M)

Costs refer to the total costs in terms of PV system installation with operation and maintenance (O&M) during the lifetime of the PV system. Based on the standard test conditions to define watt peak[144] (IRENA, 2012) of 1 kW/m^2 of solar irradiance, we concluded that 160Wp was produced by m^2 [145]; this means that 6.25 m^2 is needed to produce 1 kWp.

Therefore, the initial investment per square meter (m^2) is

$\mathbf{I_{PV=}}$ **1.9 €/Wp x 160 Wp/m^2 = 304 €/m^2.**

The O&M costs, which are usually set at 1% of the investment, should be included.

The total cost is discounted during the lifetime of PV system (20 years). The discounted cost of the PV system, C$_{PV}$ is;

$C_{PV} = I_{PV} + \sum_{N=1\ to\ 20} \frac{I_{PV} \times O\&M}{(1+r)^N}$ = **342** €/m^2 , *with r=5%, O&M=1%*

For example, for a medium-sized supermarket with 2000 m^2, the total investment amounts to €684,000.

2) Expected revenue streams

Revenues concern avoided electricity bills in the case of self-consumption, sales of PV electricity surplus, sales of green certificates (if applicable), and potentially, government support (when the PV LCOE is not yet profitable).

a) PV electricity production for self-consumption <u>without any policy support</u>

Here we assume that there is no policy support for the PV self-consumed model; e.g. no installation subsidies, no FIT, no permission for feed-in electricity to the grid. When the entire PV production is self-consumed without such supports, the expected revenue is equal to the retail electricity price avoided based on **PV electricity produced ($\mathbf{E_{PV}}$).** The discounted revenues depend on the **retail electricity price ($\mathbf{P_E}$)** changes with time. Here below, we calculate for three cases assuming change in retail electricity tariffs with different increase rate of a: a=0%, a=2%, and a=5%.

The electricity price is related to profitability. Assuming the constant E_{PV} every year, the expected revenue (=E_{PV} x P_E) is given in the Table LXXXIX. The degradation of module efficiency with time is neglected.

[144] Watt peak (Wp) refers to the peak power of a PV module or system under standard test conditions (light intensity: 1000 W/m^2, temperature: 25 ºC, and air mass: 1.5)

[145] The PV initial investment was estimated at 1.9 €/Wp in 2013 using monocrystalline PV modules with an efficiency of 16%.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Total**
E_{PV} (kWh/m^2)	3.4	5.6	11.9	16.9	19.8	21.4	21.8	18.4	13.6	8.1	4.0	3.0	**148**
P_E (€/kWh)	0.1210	0.1210	0.1210	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.0732	0.1210	0.1210	**-**
Revenue (€/m^2)	0.407	0.672	1.442	1.239	1.451	1.564	1.594	1.345	0.993	0.593	0.483	0.359	**12.1**

Table LXXXIX: Expected revenue with self-consumption in Paris (detailed calculation is presented in annex)

For example, a 2000 m^2 supermarket can save 24,200€ of annual electricity fees by avoiding power purchase from the grid.

With a discount rate of 5% (European Commission, 2013c), the discounted revenue (R_{SC}) over 20 years was calculated according to the annual increase in the retail electricity price (a);

$$R_{SC} = \sum_{N=1\ to\ 20} \frac{E_{PV} \times P_{E\ retail} \times (1+a)^N}{(1+r)^N}$$

By comparing the investment required (C_{PV}) and the expected revenue (R_{SC}), we come to the conclusion that the PV self-consumed model in French supermarkets is not yet economically attractive without policy support (see Table XC).

PV self-consumption	Investment (€/m^2)	Revenue (expected) (€/m^2)	Payback period	Investment gains/ losses over 20 years (€/m^2)
Electricity price increase (a=0%)	342	151	> 30 years	-191
Electricity price increase (a=2%)	342	177	> 30 years	**-165**
Electricity price increase (a=5%)	342	230	> 30 years	-112

Table XC: Comparison between the investment required and the expected revenue from self-consumption (*a: annual increase in retail electricity prices*)

b) *PV electricity production __under the current FIT scheme__*

We now calculate the revenue of PV system installers under the FIT system. In this case, 100% of PV electricity produced is fed into the grid with a financial compensation based on the current FIT system. The fixed tariff was set at the beginning of the 20-year long-term contract. The annual constant E_{PV} (=148 kWh/m^2) was also considered to calculate the expected revenue (R_{FIT}).

The FIT was **0.1727 €/kWh** [146] during the first quarter of 2013 (Observ'er, 2013) for commercial-sized systems above 36 kWp [147]. The discounted revenue (R_{FIT}) over 20 years was calculated with a discount rate of 5% (European Commission, 2013c).

$$R_{FIT} = \sum_{N=1\ to\ 20} \frac{E_{PV} \times FIT}{(1+r)^N}$$

$$R_{FIT} = 319\ €/m^2$$

The discounted revenue (R_{FIT}) over 20 years proves to be smaller than the required investment (C_{PV}) of €342 per m^2. In this calculation, we use the mean PV system price with uncertainties on the discount rate (r) and the differences in solar irradiance according to the location (see Table XCI). The calculation can be considered concise and the results will be different depending on the assumptions

[146] A 20 year contract

[147] The support is limited to the installation lower than 100kWc. In this study, we ignore this limitation and apply the given tariff of 0.1727€/kWh for all the sizes.

and data used. The tariff is not attractive in Paris but is sufficient in the sunniest regions located in the south of France. To make the PV system profitable, the discounted revenue (R_{FIT}) should be at least equal to the discounted investment required (C_{PV}). The general equation is:

$$C_{PV} = R_{FIT}$$

$$I_{PV} + \sum\nolimits_{N=1\ to\ 20} \frac{I_{PV} \times O\&M}{(1+r)^N} = \sum\nolimits_{N=1\ to\ 20} \frac{E_{PV} \times FIT}{(1+r)^N}$$

To make the PV system profitable in Paris, the FIT should be at least equal to the PV LCOE. The investment (C_{PV}) of €342 per m^2 with a 5% discount rate needs a minimum support of **0.186 €/kWh**[148].

Segment	Investment (€/m^2)	Revenue (expected) (€/m^2)	Payback period	Investment gains/losses during 20 year (€/m^2)
Paris with FIT	342	319	23 years	-23
Nice with FIT	342	428	15 years	+86

Table XCI: Impact of the location in France on the profitability of the FIT

3.3.3 PV policy costs and benefits from the viewpoint of policymakers

1) Policy costs: 100% PV self-consumption vs. FIT scheme

Policy support (S) is needed to make the proposed model profitable. Here below, we attempt to formularize the financial support to give economic incentives to end-users to install PV systems on their roof for the purpose of 100% self-consumption. This support is decided by the country and can be conducted via different policy instruments, e.g. direct installation subsidies or a long-term contract. In our calculation, we assume that PV LCOE is equal to the FIT (0.1727 €/kWh).

$$S = I_{PV} + \sum\nolimits_{N=1\ to\ 20} \frac{I_{PV} \times O\&M}{(1+r)^N} - \sum\nolimits_{N=1\ to\ 20} \frac{E_{PV} \times P_{E\ retail}}{(1+r)^N}$$

Equation 2: Necessary financial support for PV self-consumption

	Policy costs under 100% self-consumption	**Policy costs under FIT scheme**
Annual policy costs of the support	€ 215 million	2.36 TWh x 0.1727 €/kWh = €408 million
Discounted policy costs of the support over 20 years	16 million m^2 x 165 €/ m^2 = €2.6 billion (a=2%)	16 million m2 x 319 €/m2 = €5.1 billion

Table XCII: Financial support to apply the PV self-consumed model and the FIT model

Table XCII shows the minimum policy support needed based on two different policy systems: 100% PV self-consumption vs. FIT scheme. We have found that PV electricity production using the 100% self-consumption model is less expensive for policymakers compared with the FIT system.

[148] Author's calculation

2) Benefits of PV installations: 100% PV self-consumption vs. FIT scheme

PV power can be an interesting option to increase the part of renewable energies in the final gross energy consumption. Table XCIII explains general benefits from PV installations in terms of energy transition. Those benefits are the same regardless of the type of policy support.

Energy transition (See 3.3.1.)	**Possible installations**: 16 million m^2 x 160 Wp/m^2 = **2.56 GWp** (47% of the current installations)
	Electricity production: 16 million m^2 x 148 $kWh/m^2/year$ = **2.36 TWh/year** (0.5% of the total electricity consumption of 447 TWh (Eurostat))
CO_2 emission avoided	GHG emission reduction: little impact with the large part of nuclear power in France (Cruciani, 2014)

Table XCIII: Expected benefits of the PV self-consumed model and policy support

However, the proposed 100% self-consumption model give more benefits in terms of grid impacts and land usage compared to other PV system usages under FIT (e.g. utility-scale PV systems) (see Table XCIV).

Land usage	16 million m^2 available **without new land use**
Local grid pressure reduction	No **grid reinforcement** needed and electric power transmission and distribution (T&D) losses avoided the summer peak is reduced by about 880 MW (16 million m2 x 55 W) In the future, at 10% PV penetration, systemic costs related to grid management can be reduced by up to around 30% (22% saved for grid reinforcement and 8% saved for balancing with a larger geographical spread).

Table XCIV: Additional benefits from the proposed 100% self-consumption model compared to other PV usages (e.g. utility-scale PV systems)

3.4 Impacts on key stakeholders

The proposed PV self-consumption model reduces the purchased electricity from the grid, influencing the profits of energy market players such as utility generators and grid operators. In addition, as more people install PV systems for self-consumption to lower electricity bills, other end-users who continue to use electricity from the grid will pay increased electricity rates to cover the same amount of CSPE or the fixed costs of grid investment (IEA, 2014; 2014b; IEA-RETD, 2014). In this regard, we expect revenues losses of stakeholders as the share of PV power based on self-consumption model increases in the electricity system.

Therefore, we now intend to investigate the proposed model's impacts on stakeholders. Taken the significance of influence into account, we focus on latent group to calculate those losses. Our analysis also gives a comparison between the proposed 100% PV self-consumption to the current policy scheme, FIT. This aims to demonstrate the real costs of PV power in the electricity system under two different policy configurations.

This analysis can help policymakers to prepare the strategy towards PV self-consumption model in the electricity system. Policymakers should examine expected impacts on other stakeholders' interests to mitigate policy risks or threats. Below, the possible impacts are quantified to anticipate policy risks.

3.4.1 Impacts on stakeholders' interests under 100% PV self-consumption model

In case of self-consumption, the impact on stakeholder interests can be roughly calculated by reviewing changes in electricity bills with the penetration of the self-consumption model in the electricity system. The losses can be calculated by multiplying the electricity tariff for each segment by the electricity avoided from the grid (see annex):

E_{PV} (kWh/m^2) x the part of electricity tariff ($P_{stakeholder}$) (€/kWh) = Revenue losses $_{stakeholder}$ (€/m^2)

Due to reduced purchasing from the grid, end-users who own PV systems use less electricity from the grid. The existing power plants and grid operators will earn less revenue. In addition, end-users will pay more for the same amount of CSPE. The government will have less tax revenues. In this study, the government's reduced tax revenues from VAT are excluded because French supermarkets do not pay VAT. However, this impact is notable in the residential sector with 20% of VAT.

In addition, since the proposed self-consumption model in French supermarket sector is not yet profitable, further financial support is needed to realize it. Additional policy costs would thus be generated, if the government decides to promote the proposed 100% PV self-consumption model. The type of support will depend on the policy decision. Therefore, the stakeholder concerned in terms of policy support would be different according to the decision. Furthermore, as indicated, the relatively positive impacts on grid management caused by 100% self-consumption model should be considered. The Table XCV captures the expected impacts on each stakeholder.

Stakeholders' revenue losses caused by the increase of 100% PV self-consumption in electricity system			
Electricity tariff segment	Stakeholder concerned	Amounts by m^2 of installation (annual)	Nation-wide amount (annual)
Conventional electricity production decrease	**Utility generators**	4.31 €/m^2	€69 million
TURPE (network)	**Distribution**	4.31 €/m^2	€69 million
CSPE	**End-users** of electricity	2.88 €/m^2	€46 million
CTA	Retired electricity employees / **Government**	0.38 €/m^2	€6.0 million
TCFE	Local **government**	0.25 €/m^2	€4.1 million
Total		**12.14 €/m^2**	**€194 million**
Impacts on grid management	**Grid operators**	Positive impacts on grid-level costs (systemic costs can be reduced)	
Policy support to 100% self-consumption model	Depending on policy choice	13.4 €/m^2	€214 million

Table XCV: Impacts on stakeholder interests of 100% self-consumption model (see annex)

3.4.2 Impacts on stakeholders' interests under FIT scheme

By using *the FIT scheme*, PV producers continue to pay all taxes and fees. However, with the penetration of PV electricity production, the existing power generators will sell less electricity in the market, thus leading to reduced sales revenue for other power generators. Moreover, the financing of the FIT is supported by the CSPE from the electricity rates. Possible impacts on stakeholder interests are calculated in Table XCVI.

Stakeholders' revenue losses under FIT			
	Stakeholder concerned	Amounts by m^2 of installation (annual)	Nation-wide amount (annual)
Conventional electricity production decrease	**Utility generators**[149]	4.31 €/m^2	€69 million
Policy support to FIT Financing via CSPE	**End-users** of electricity	€25.56/m^2 [150]	€408 million [151]

Table XCVI: Impacts on stakeholder interests of the FIT scheme

3.4.3 Comparison of PV integration under FIT vs. 100% PV self-consumption model

Based on the above calculations, we have found that the same level of cost exists under the FIT system and 100% PV self-consumption model to make the PV system profitable. However, there are important differences. Below **Figure 75** shows the real costs of PV power in the electricity system based on the concept of systemic costs (see Part I chapter 2).

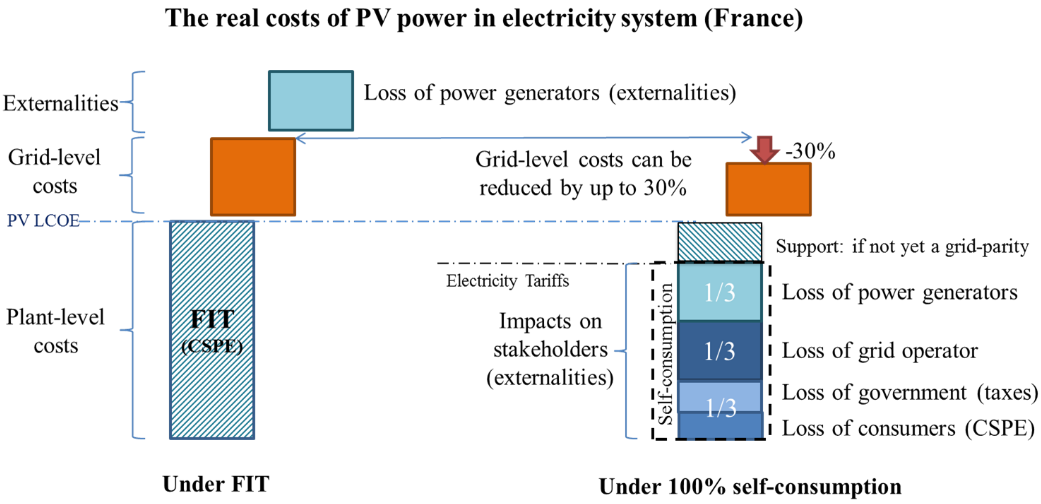


Figure 75: The real costs of PV power in the electricity system (France)

First, under FIT system, PV electricity is supported by fixed tariffs based on long-term contracts and this is directly financed by CSPE, placing the burden mainly on end-users. We have seen the rapid increase in electricity retail tariffs in France and Germany mostly due to the contribution of CSPE and EEG respectively. As seen, the financial support to the energy transition has increased retail prices and there are now issues about energy poverty and industrial competitiveness (see Part II). However, PV self-consumption model with its good correspondence ratio requires **less direct financial support** and electricity bill savings make up the profitability of the model.

[149] See Table CXIII & annex in terms of the calculation of reduced sales revenue for producers
[150] 148 kWh/m^2 x 0.1727 €/kWh = €25.56/m^2
[151] 2.36 TWh/m^2 x 0.1727 €/kWh = €408 million

Secondly, the use of PV electricity under FIT scheme has the bigger cost of PV power in the electricity system than under 100% PV self-consumption model. The total sum of PV integration in the electricity system under FIT scheme adds the policy supports for purchased PV electricity, additional grid-level costs, and potential revenue losses of exiting utility generators (externalities). However, under the PV self-consumption model, the loss of existing power plants (externalities) becomes more visible. If the government decides to use a political instrument like PV taxes when PV becomes very competitive in the future, **the externality related to the losses can be internalized.**

In addition, under FIT system, PV system installers do not have economic incentives that match their real consumption profile; instead, there can be a windfall effect for profit-seeking (see Part II chapter 3). Uncontrolled installations require further policy support, leading to an increase in the CSPE. However, PV self-consumption under a well-designed policy framework can **incite people to maximize the ratio of onsite self-consumption, thus avoiding such windfall effects.** This will lessen the policy costs.

However, PV self-consumption model gives stakeholders negative externalities of revenue losses (they correspond to avoided electricity consumption from the grid). According to our analysis, **revenue losses are widespread among stakeholders** under PV self-consumption model. Therefore, under this model, we gain a **clearer overview of the impact of PV integration on each stakeholder** than under FIT. This clear overview allows the government to design policy actions in a shrewd manner to address potential policy risks.

Furthermore, the proposed 100% self-consumption model can contribute to minimize additional grid-level costs. It also cuts the peak demand level during summer at midday thanks to the possibility of the full self-consumption. This would be useful to reduce backup costs in countries with peak demand in the summer. However, it is extremely important to prepare a fair scheme to finance the grid to maintain the security of the national electricity system.

4 PV self-consumption in French residential sector (2030)

4.1 Introduction

In the previous section, we studied opportunities of PV self-consumption when it is entirely consumed onsite. In this section, we extend our case study in the longer-term perspective (2030). We aim to explain how the technological progress affects the usage of PV systems in the future. In this context, our study focuses on the impact of PV self-consumption combined with batteries in the residential sector. As said, the residential sector has a poorer correlation between PV power output of PV systems and electricity consumption profile without storage system. However, the correlation in the residential sector can be improved by combining with the storage system in the future. The continuous price decline in the battery solution can induce the transition to PV self-consumption in the residential sector.

As residential PV systems coupled with batteries become more competitive, end-users will be more willing to switch to the self-consumption of PV electricity instead of purchasing power from the network. However, as seen in section 2, the transition to PV self-consumption gives impacts on all stakeholders in electricity market. Governments must prepare the transition towards PV self-consumption to maintain the security of the national energy system. It is thus necessary for policymakers to understand the timing of this transition.

In this context, this study attempts to evaluate the economic attractiveness of French residential PV systems coupled with batteries using the learning curve approach in the near future. It includes three steps; the first step defines the optimum battery size to achieve a significant level of PV self-consumption in the residential sector (4.3). The second step predicts the price variation in the French residential PV systems in 2030. We calculate the PV LCOE in 2030 based on the International Energy Agency (IEA) scenarios using the estimated costs of Li-ion batteries. We then compare them to the estimated price of electricity[152] in 2030 (4.4). Finally, we quantify PV installation opportunities and the loss of network funding caused by the transition to PV self-consumption (4.5).

4.2 The ratio of self-consumption in the residential sector

The good correlation between PV power output and consumption profile is important to define economics of PV self-consumption model. We have seen that the entire consumption of PV power output is only possible for some sectors like supermarkets (section 3). The weak correlation (~ 30-40% without storage) in the separate residential sector can be increased via some methods.

The first method is to modify the demand profile to better match the PV power output to the electricity consumption (demand response). It is possible with some equipment such as electric hot water heaters or some electric home appliances. This method is limited because home appliances (e.g. oven, hotplate, television, etc.) operate at about the same time every day and it requires the use of advanced IT technologies.

The other method is to store electricity not consumed to release it when there is demand. This method requires the use of batteries and increases PV system prices. The system is rarely profitable for the moment; the high costs of battery technology are the main barriers for the large deployment of PV systems coupled with batteries (see Part I chapter 2). We have seen that the cost of batteries is expected to decline in the future. This gives the potential of large-scale deployment of PV systems.

4.3 The optimal size of PV systems coupled with batteries in the residential sector

We now want to define the optimum battery size to achieve a significant level of PV self-consumption in the residential sector.

A smaller production system of PV electricity compared with the electricity demand is more likely to be completely self-consumed without storage solution, but the final gains with respect to the total electricity consumption (the avoided power consumption from the grid) will be small. However, a large PV system will require a large storage system, and thus leading to a high additional cost. An optimization to define battery size to combine with PV systems for self-consumption is necessary.

[152] There are a number of challenges because France has quite low electricity tariffs and insolation.

In order to define the optimal level of battery size combined with PV systems, our study is based on a few studies in Germany (Weniger, et al., 2014; Huld, et al., 2014; Partlin, et al., 2015).

T. Huld examines 144 residential PV systems with batteries in Ulm, Germany. It shows the average links between the level of PV self-consumption and the capacity of installed PV systems without batteries in case of electricity consumption of 3000 kWh/year (Table XCVII):

PV power production level compared with electricity consumption	PV self-consumption ratio
PV power production = electricity consumption	20% ~30%
PV power production = 1/2 electricity consumption	40% ~ 50%
PV power production = 1/3 electricity consumption	80% ~ 90%

Table XCVII: Ratio of self-consumption according to different residential PV system sizes

The study also indicates that the level of PV self-consumption does not increase much even though several housing with PV systems are grouped together to make a larger residential area for self-consumption of PV electricity. It is because each residence shares a similar electricity consumption profile. The use of batteries is therefore necessary to increase the level of PV self-consumption. The study provides the ratio of self-consumption with different sizes of Li-ion batteries for residential applications (see Table XCVIII). When the size of batteries changes from 3 kWh to 6 kWh, the level of PV self-consumption ratio will increase only by around 10%.

	Without battery	3 kWh battery	6 kWh battery
PV self-consumption level	35% ~60%	70% ~85%	80% ~ 90%

Table XCVIII : PV self-consumption ratio according to different battery sizes coupled with 1 kWp residential PV systems

The study by S. Partlin defines the optimal combination of PV systems with batteries in Germany. The experimental study was conducted in Germany for 12 months based on 120 residential PV systems with high performance Li-ion batteries (the most common systems in Germany). It indicates that 80% of households consume less than 4000 kWh/year of electricity. It shows that the use of 3 kWp PV systems with 2 kWh Li-ion batteries for residential applications is optimal for 80% of the households achieving up to 90% of PV self-consumption.

The study of T. Weiniger defines the mean ratio of PV self-consumption according to the size of PV system and the capacity of batteries, which are normalized to the annual electricity demand in MWh. The study indicates that the use of 3 kWp PV systems coupled with 4 kWh Li-ion batteries achieves around 80% of self-consumption for average households.

In our study, we assume that the use of 3 kWp PV systems coupled with 4 kWh Li-ion batteries for residential applications are optimum reaching 80% to 90% of PV self-consumption.

4.4 The trend of PV system prices coupled with batteries

In this part, we aim to demonstrate the evolution of residential PV system prices coupled with Li-ion batteries in 2030. In Part I, we have presented different IEA's scenario. According to IEA's hi-Renewables scenario (hi-Ren), the installed PV capacity will achieve 1721 GW in 2030, generating 2370 TWh of electricity in 2030. We also gave Li-ion battery prices based on some projections (see Part I chapter 2). Our study calculates the projected PV LCOE in 2030 based on the learning curve approach. IEA's PV deployment scenarios were used to estimate the PV market size in 2030. Our study assumes a current battery price of $500/kWh including installation costs[153] and a cost of $150/kWh for 2030. We calculate the PV LCOE in 2030 using the estimated costs of Li-ion battery and compare it to the assumed price of electricity in 2030.

In order to calculate the PV LCOE in 2030, we need to estimate PV system costs in 2030. In order to calculate it, we use an average current cost of $ 3.1/Wp for the PV residential systems[154] (IEA PV Roadmap 2014). We then calculate the PV system costs in 2030 using the learning curve with a learning rate of 18% (IEA, 2014, p. 18). Our calculation is based on IEA's three scenarios which give the prospect with regard to world PV installations in 2030 (see Part I chapter 4).

- 6DS scenario
- 2DS scenario
- IEA's hi-Ren scenario (IEA, 2014)

We estimate the residential PV system costs in 2030 from 1.5 $/Wp (hi-Ren scenario) to 2.19 $/Wp (6DS scenario).

	2013	IEA's scenarios for 2030		
		6DS	2DS	HiRen
World PV cumulated installations (GWp)	135	451	842	1721
Residential PV system cost ($/Wp)	3.1	2.19	1.84	1.5

Table XCIX: Estimated PV system costs in 2030 (based on IEA's scenarios)

We then add the cost of 3 kWp PV systems to the cost of 4kWh batteries:

Material costs	2015 (2013 for PV)	IEA's scenarios for 2030		
		6DS	2DS	HiRen
4 kWh batteries	2000 US$	600 US$	600 US$	600 US$
3kWp PV systems	9300 US$	6570 US$	5520 US$	4500 US$

Table C: Estimated costs of 3kW PV systems coupled with 4kWh batteries in 2030 (based on IEA's scenarios)

The lifetime of PV systems is 20 years and the lifetime of batteries is 10 years (we consider the same cost for changing the battery). We use a discount rate of 5%. The PV LCOE varies according to the irradiation. We obtain the results for PV LCOE as below (c$/kWh):

Irradiation (kWh/kWp/year)	2013	IEA's scenarios for 2030		
		6DS	2DS	HiRen
1000	36.7	22.6	19.0	16.2
1500	25.5	15.1	12.7	10.8

Table CI: Estimated PV LCOEs in 2030 based on IEA's scenarios

The radiation in France and in Germany is around 1000 kWh/kWp/year: Berlin is about 900 kWh/kWp/year and Paris is 960 kWh /kWp/year.

The electricity tariffs for households in 2014 are: 20.2 cUS$/kWh in France and 38.0 cUS$/kWh in Germany (1 US$=0.784€). In our calculation, we assume that the electricity tariffs increase by 2% per year until 2030.

[153] Tesla sold 7 kWh batteries at 3000$ and 10 kWh batteries at 3500$. The Deutsche Bank estimated the prices at 500 $/kWh including installation costs (TECSOL, 2015).
[154] The average PV system costs of IEA-PVPS countries.

Electricity tariff (c$/kWh)	2014	2030 with a 2% increase by year
France	20.2	27.7
Germany	38	52.2

Table CII: Electricity tariffs in France and Germany in 2030 with a 2% increase by year

We then calculate the PV LCOE and the profitability of PV systems with batteries which vary depending on the level of PV self-consumption. The estimated PV LCOE in 2030 and the profitability of PV systems with batteries (the electricity price divided by the PV LCOE) are shown as below:

1000 kWh/kWp/year		2013	2030		
			6DS	2DS	HiRen 2030
80% of PV self-consumption	**PV LCOE**[155]	**45.9**	**28.4**	**23.6**	**20.3**
	Profitability Germany	0.8	1.8	2.2	2.6
	Profitability France	0.4	1.0	1.2	1.4
90% PV self-consumption	**PV LCOE**	**40.8**	**25.2**	**21.0**	**18.0**
	Profitability Germany	0.9	2.1	2.5	2.9
	Profitability France	0.5	1.1	1.3	1.5

Table CIII: Profitability of PV systems with batteries in 2030

It should be noted that even by adding the cost of batteries, PV systems are currently close to profitability in Germany and they would become almost competitive in France by 2030 under all IEA scenarios with a self-consumption rate of above 80%. However, if the global number of PV installations grows faster than the IEA scenarios assumptions or if targeted policies to reduce soft-costs are implemented, residential PV systems with batteries can become profitable in France before 2030, especially in the southern part of France with a higher insolation.

In addition, battery prices are expected to continue to decline. Our analysis shows that battery prices will represent a small fraction of the cost of residential PV systems combined with batteries. Based on the business as usual scenario (6D), it will only account for 11% of the total installed cost of PV systems amounting to only 2.5 c$/kWh in 2030. With a self-consumption rate of above 80%, the surplus electricity is small. If PV policies aim to promote self-consumption, it is conceivable to establish a mechanism for reselling the surplus to the network in order to enhance its economics (e.g. net-metering).

[155] The PV LCOE is weighted by the self-consumption level (PV LCOE with 80% of self-consumption = PV LCOE/80%)

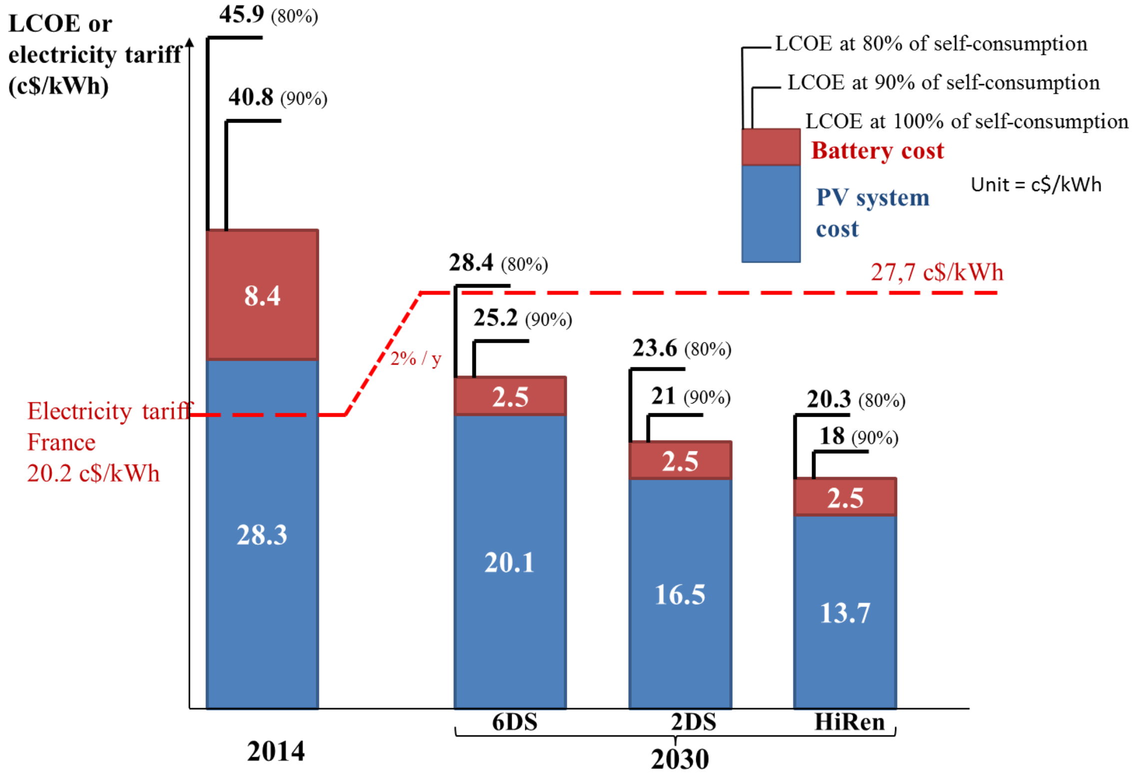


Figure 76 : Economic feasibility of residential PV self-consumption model combined with batteries in 2030

4.5 PV growth opportunities and network funding losses

A simple calculation based on PV systems coupled with Li-ion batteries gives an upper limit of PV development opportunities in French residential sector. France has 33.4 million of residential buildings in 2012, including 18.8 million individual houses (ADEME, 2013, p. 36) and the residential and tertiary sectors account for 44% of the national electricity consumption.

We assume that an average capacity of 3 kWp PV systems coupled with 4 kWh Li-ion batteries were installed on 18.8 million individual houses in France. This represents potential installations of approximately 56 GWp producing PV electricity of about 56 TWh per year (56 GWp x 1000 kWh/kWp/year). This accounts for more than 12% of French electricity production (447 TWh in 2014).

In addition, with the important level of self-consumption, PV self-consumption model in the residential sector can limit additional grid-level costs related to grid reinforcement. Furthermore, PV power fluctuation smoothing via a wider geographical spread can reduce balancing costs compared with utility-scale PV systems. In Part II, we have seen that the estimated addition grid-level cost with 10% PV penetration in France is 27$/ MWh (incl. 6 $/MWh for grid upgrading and 2$/MWh for short-term balancing). The calculated opportunities of PV self-consumption in the residential sector represent almost the same level of PV penetration. Based on this smart approach, the proposed applications of residential PV systems with batteries can reduce the grid-level costs by a maximum of 30% compared with the PV power use with no strategy. However, we have seen that the backup costs in France are significant with an important level of PV penetration because the peak demand of electricity appears usually in the winter evening; 19 $/MWh at 10% PV penetration. The backup costs remain the same for other PV usages (i.e. FIT). Therefore, in order to produce electricity of 56 TWh/year, an additional cost of $ 1.1 billion can be expected.

However, as seen, it must not be forgotten that PV self-consumption induces the loss related to network funding (the loss of grid operator revenues). In the previous section, we discovered that one third of electricity tariffs in France are used for grid funding. This amounts to around 6.1 c$/ kWh[156]. If the annual PV power output of 3000 kWh (3kWp x 1000 kWh / kWp/year) is entirely self-consumed, the loss of grid funding will amount to 183 $/year (6.1 c $ / kWh x 3000 kWh). In this regard, if all individual households in France were equipped with PV systems with batteries, a loss of grid funding amounting to $ 3.4 billion / year (18.8 million x 183 $/year) can be expected. If the loss of network funding is distributed to end-users of electricity from the grid, the cost will be 0.8 c$ / kWh ($ 3.4 billion / (447 TWh – 56 TWh)). Taken such impacts into account, the fair mechanisms should be considered to finance the grid.

Energy transition	**Possible installations**: 18.8 million houses x 3 kWp = **56 GWp**
	Electricity production: 56 GWp x 1000 kWh/kWp/year = **56 TWh/year** (12% of the total electricity consumption of 447 TWh (Eurostat))
CO_2 emission avoided	GHG emission reduction: little impact with the large part of nuclear power in France

Table CIV: Expected benefits of the PV self-consumed model in residential sector

Land usage	392 million m^2 available **without new land use** ($7m^2$/kWp, cf. Part I chapter 2)
Impacts on grid-level costs	No **grid reinforcement** needed **Addition grid-level costs can be reduced by up to 30%**

Table CV: Additional benefits from the proposed self-consumption model in residential sector compared with other PV usages (e.g. utility-scale PV systems)

PV self-consumption costs (losses of grid funding and taxes)	**Direct policy cost for FIT**	
	Under hi-Ren scenario	Under 6DS scenario
$ 3.4 billion for the grid + $ 3.8 billion for taxes[157] = $ 7.2 billion	$ 7.6 billion by year	$ 11.3 billion by year

Table CVI: Losses of grid funding and taxes under PV self-consumed model vs. FIT costs to support the same level of PV installations

The costs to promote PV installations via PV self-consumption are less than the FIT remuneration[158]. In order to install PV capacity of 56 GWp without batteries, FIT support would be $ 7.6 billion by year[159] (13.7 c$/kWh x 56 TWh) under the optimistic HiRen scenario and $ 11.3 billion by year[160] (20.1 c$/kWh x 56 TWh) under the BAU scenario (6DS).

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[156] 1$ = 0.784€
[157] Taxes represent 6.8 c$/kWh in residential electricity tariffs (34% of the electricity tariffs). The annual cost: 6.8 c$/kWh x 3000 kWh x 18.8 million
[158] Especially if a tax reform is done to refund tax losses induced by PV self-consumption
[159] Equivalent to 1.7 c$ / kWh distributed to all electricity consumers from the grid
[160] Equivalent to 2.5 c$ / kWh distributed to all electricity consumers from the grid

5 Policy recommendations

As PV system prices with the battery decline, there will definitely be a political pressure from the electricity consumers to encourage PV self-consumption. The state must prepare solutions to control impacts on the system (e.g. network management). In this regard, it is important to define policy strategies towards PV self-consumed model. Those strategies should be prepared based on the participation of key stakeholders. Here, we have attempted to define possible strategies for PV self-consumption model development.

1. Giving priority to PV installations with the best corresponding profile between onsite demand and PV system output

We have seen that PV self-consumption model can maximize benefits with the best correspondence between onsite demand and PV system output, encouraging better returns on investment than in poorly corresponding areas. First, policy should promote targeted areas with the best correlation between onsite consumption and PV power output like supermarkets. In addition, local PV production can be consumed locally to increase the self-consumption ratio at the local level. The PV self-consumed model may provide a good solution for congested regions or areas with grid problems. In addition, the development of such sectors based on 100% self-consumption has much value because it gives policymakers a large-scale experience of PV self-consumption to anticipate risks and impacts on the whole electricity system.

2. Increasing the correspondence profile between onsite demand patterns and PV production

Sectors with poorer correlation can be promoted in line with the demand-side response to obtain optimal correspondence between PV power production and PV self-consumption (IEA, Op. cit.). The results will smooth the PV injection peak during the PV generation peak, thereby reducing the impact on the power grid system. Smart grids may provide a dynamic policy instrument to improve correspondence between demand profiles and the production pattern, based on a more responsive grid system. They are designed to better control load managements by improving the transparency of the electricity market. As seen, improving the storage solution is a good way to improving the correspondence.

3. Preparing strategies to minimize the economic losses of key stakeholders (the latent group)

We have analyzed impacts on stakeholders' interests caused by the penetration with the PV self-consumption model. Policymakers should prepare policy actions to address those issues.

Utility generators

With the penetration of intermittent energies with low marginal production costs, the recovery of fixed investment costs for power generators becomes a concern. In order to maintain a certain level of dispatchable generation capacity in the energy mix, it is important to make conventional power plants, which are essential for the grid balancing, economically viable though policy supports (e.g.

capacity payment) (IEA, 2014b). However, when the policy presents a long-term vision, utility generators can explore new business opportunities by diversifying their business areas. In addition, it is important to have a regular and progressive policy in terms of the transition to PV self-consumption in the future with the objective to 1) give enough time for traditional electricity producers to adapt to the new market situation, 2) reduce the negative impacts on the electricity mix by adapting to the age of production capacity in use.

Grid operators

The impact on the network cannot be ignored. The planning of PV deployment had better be done based on the expertise of the grid operator. Under the self-consumed model, preparing a fair scheme for grid cost recovery is necessary to justify the development of this model (IEA, 2014; 2014b; IEA-RETD, 2014). The fixed cost recovery of grid investment should be addressed via a fair allocation scheme among users. The increased fixed tariff or redesigned electricity tariffs (e.g. demand-based charges, time-based pricing) can be considered (IEA, 2014; 2014b). Further costs can arise in terms of grid extension and upgrading. However, as said, the 100% self-consumption by targeting areas with the best correspondence (e.g. supermarkets) will reduce pressure on the grid without additional investment for grid extension or upgrading.

End-users

Government policy decisions concerning the energy transition are mainly supported by end-users via CSPE or EEG. However, as seen in section 3, the PV self-consumption model contributes to visualize the energy transition costs with a widespread distribution among stakeholders. In this case, it would be easier to control the increase in electricity rates. Otherwise, additional revenue creation can be considered to finance the PV self-consumed model: e.g. renewable energy certificates (RECs) or carbon tax.

4. Allowing connection to the grid with a proper compensation scheme

The permission to connect to the electricity network is currently needed to secure the reliability of PV systems. The rules and regulations regarding grid connection will play a key variable in the economics of the model affecting prosumer decisions for usage (IEA-RETD, 2014). In the long term, the PV self-consumed model can be developed by disconnecting from the grid when the storage system becomes economically viable for users. However, before this happens, the PV self-consumed model needs policy support which allows for grid connection with proper economic compensation. The compensation level, type and amount will vary according to the country's policy decisions. When policy strategy decides to promote self-consumption of PV power putting stress on benefits, PV policies can focus on improving the economics of self-consumption model, e.g. reduction in non-module costs, no VAT on self-consumed electricity.

5. *Establishing long-term policy vision*

The national policy strategy - whether to encourage or prevent the use of such a model - will determine the level of promotion of the PV self-consumed model in the energy mix. This policy strategy should present *a long-term vision* to give all stakeholders time to prepare to the change with PV self-consumption in the electricity system. The organizational changes should be taken place under the new regulatory system to introduce new business practices and grid models. The future PV policy should be decided based on systemic perspective taken the costs for the whole energy sector into account (*coût d'une decision*) (Riveline, 2005).

6 Conclusions

PV self-consumption model based on a proper mechanism can provide a sustainable way of using PV power by benefiting PV system's advantage of being able to provide decentralized power. This also gives opportunities to share the cost of energy transition among stakeholders compared with FIT system. In addition, the grid-level costs related to the intermittency of PV energy can be minimized when the PV energy based on the self-consumption model is strategically used.

From a strategic perspective, in the short-term, the PV self-consumed model should be applied in sectors with the best mating ratio between the load profile of electric consumption and PV power production, so as to gain the best results. In the future, as electricity prices continue to rise while PV system prices go down, the PV self-consumed model will benefit from better conditions for its application. The economics of the PV self-consumed model will greatly improve, making the model profitable for other sectors whose correspondence ratios are poorer, e.g. residential. The impacts would be greater when it is combined with improved storage systems. Before achieving the level, current policy should aim to prepare targeted strategies for each sector, e.g. residential, commercial and industry, so as to achieve the best results.

We provided an in-depth analysis of PV self-consumption use in the electricity system. From the short-term time period (2020), our analysis proposed to develop PV self-consumption model by using the existing surfaces of supermarkets because of possibilities of 100% self-consumption. When it is entirely consumed onsite, the grid reinforcement is not needed and electric power transmission and distribution losses can be avoided. This leads to less systemic costs compared with other PV development model (e.g. utility-scale PV systems based on FIT system). In addition, it does not require additional cost of land use. We also demonstrated that 100% PV self-consumption requires less direct financial support than FIT system. PV self-consumption model under a well-designed policy framework can incite people to maximize the ratio of onsite self-consumption. This helps avoid windfall effects. However, PV self-consumption model gives stakeholders negative externalities of revenue losses. Those revenue losses are widespread among stakeholders. It indicates that the energy transition cost can be distributed among stakeholders under PV self-consumption model unlike FIT system. Our analysis gave a detailed overview of impacts of PV integration on each stakeholder. This approach would be helpful for policymakers to estimate potential risks and to prepare policy actions to address them. Furthermore, the development of this sector gives a large-scale experience of PV self-consumption to anticipate impacts on the whole electricity system.

In the longer-term, the study has shown that residential PV systems with batteries could become profitable in France by 2030. The demand in the residential sector would thus be natural in the next 15 years in France. It is also possible to advance the timing by improving the PV economic competitiveness through targeted policies (e.g. non-module sector).

In this regard, the demand in PV self-consumption would be naturally created in the future. Policymakers will have to prepare this change. It is very important to prepare a regular and progressive policy for the transition to PV self-consumption. It should enable concerned stakeholders to have enough time to adapt to the new market situation. In addition, the policy would put more focus on limiting systemic impacts of PV power in future. How policymakers prepare this change with a proper institutional framework supported by long-term vision will affect the success of the PV integration.

Chapter 2. Dynamics of PV policy mechanisms in the international context

In this chapter, the complexity and dynamics of PV policy system in the international context is studied. It is difficult to manage the PV policy mechanisms because of its complexity and dynamic features. The difficulties get bigger in the international political context. The national PV policy mechanisms interact with other country's systems. The PV policy system is in a state of flux. The ignorance of leverage of external factors (context) of PV policy system can bring unexpected policy results in an open economy system. Therefore, a quick response to a dynamic market change is closely associated to success of PV policies.

In this context, in this chapter, we attempt to provide a precise insight on the globalization effects on the PV policy mechanisms. We aim to model the complicated strategic interactions and accompanying consequences based on the coupling case studies of Germany and China using the strategic trade theory. The change in market equilibrium influenced by the external factors is explained using the international trade theory. We intend to analyze the relations between Chinese strategic movement and the current PV industry crisis and long-lasting trade disputes.

First, we provide theoretical background of our methodology (section 1). Our approach is based on strategic trade theory to explain how a government's intervention to protect the domestic industry influences the global market mechanisms. In order to compare the situation of German market balance before and after the Chinese inputs, we use the international trade theory (section 2). In section 3, we analyze characteristics of the global PV market as the policy context. And then, a detailed analysis of Chinese strategic trade movement based on the strategic trade policy theory is presented. Our analysis explains how Chinese government's strategic trade policy influences the investment choices and payoffs of the market players. At the end, we give a new game setting to think over the possibility of increased market players' profits in the future.

1 Theoretical background

1.1 Game theory

Game theory concerns multi-party decision-making; it analyses strategic interactions among rational and independent multi-agents. The game theory explains individuals' strategic choices to maximize their profits. The utilization of game theoretical approach allows depicting complex strategic situations in a very simplified setting.

The concepts of game theory provide a language to formulate, structure, analyze, and understand strategic scenarios (Turocy & von Stengel, 2001). Game theory has been used in many different fields like economics, political science, military strategy, intentional relations, psychology, and biology and so on. For example, ***non-cooperative game theory*** has become an important tool for analyzing strategic interaction between players when decision makers act independently without being able to contract each other's actual behavior. This has found many applications in the field of industrial organization (Tirole, 1988).

Game theory exists as a unique field of science since the mid-1940s with the contribution of John von Neumann and Oskar Morgenstern. The history of game theory throws back to the publication of Theory of Games and Economic Behavior by John von Neumann and Oskar Morgenstern in 1944 (von Neumann & Morgenstern, 1944; Hillas, et al., 2014; Kim, 2014). This book provided much of the basic terminology and problem setup that are still in use today (Turocy & von Stengel, 2001); the method for finding mutually consistent solution for 2-person zero-sum games was presented (Kim, 2014).

In the early 1950s John Nash proposed a definition of equilibrium (Nash equilibrium) (Nash, 1950; 1950b; 1951; 1953)[161] and this concept built a theoretical ground of non-cooperative game theory. Nash equilibrium defines a set of strategies such that no player has an incentive to deviate from his or her action chosen after considering an opponent's choice. Merrill M. Flood and Melvin Dresher (1950) have discussed the prisoner's dilemma. In the 1950s, the concept of the core, the extensive form game, fictitious play, repeated games, matching games and the Shapley value were developed (Kim, 2014).

Reinhard Selten has introduced the subgame perfect equilibria in 1965; this was the refinement of the Nash equilibrium. Then John Harsanyi developed the concept of complete information and Bayesian games. This prepared the theoretical basis of information economics.

In the 1970s, game theory has been applied extensively in other sectors like sociology and psychology, and established links with evolution and biology. In 1972, John Maynard Smith developed evolutionary game model and introduced the concept of an Evolutionary Stable Strategy (ESS). In 1973, Michael Spence presented a signal game model with an analysis of job market signaling (Spencer, 1973) and David M. Kreps further developed this concept to screening game. In 1974, Robert Aumann (1995) introduced a correlated equilibrium, a more general solution form than Nash equilibrium.

In 1982, David M. Kreps and Robert Wilson developed further the concept of a subgame perfect equilibrium to subgame in the extensive form with imperfect information (sequential equilibrium). In 1982, Rubinstein studied a non-cooperative bargaining game. He shows that the subgame perfect equilibrium is unique when each player's cost of time is given by some discount factor. In 1988, John C. Harsanyi and Reinhard Selten produced the first general theory of selecting between equilibria providing criteria for selecting one particular equilibrium point for any non-cooperative game (Harsanyi 1988). Jean Tirole contributed to apply game theoretic thinking to analyze the dynamics of industrial organizations (e.g. decisions in setting prices price setting, investment decision) (Tirole, 1988).

[161] Finite games have an equilibrium point at which all players choose actions which are best for them given their opponents' choices.

1.2 International trade theory

Economists have thought over the gain from trade. Adam Smith (absolute advantage) (Smith, 1776) and David Ricardo (comparative advantage) (Ricardo, 1817) defended free trade's benefits in opposition to European mercantilism. According to David Ricardo, both countries gain from free trade based on comparative advantage; he was against the Corn Laws asserting that free trade flourishes the economy. The thoughts of Adam Smith and David Ricardo suggested the basis of free trade theory and the rise of neo-classical economics has further developed the theory; the fundamental thoughts on free trade are maintained but the scope of application was extended sometimes based on the refinement (e.g. Heckscher-Ohlin model (Heckscher & Ohlin, 1991)). Free-trade theory became an important assertion (Bhagwati; Bhagwati, 2002; 2004) in terms of guidelines of international trade.

On the contrary to this, the argument of advocates of protective trade is that economic policy should support or protect domestic industries from international competition. There are other approaches to explain the occurrence of international trade; e.g. product cycle theory (Vernon & Wells, 1966; Vernon, 1979) and product differentiation theory (Krugman, 1980; 1981; 2008).

Free trade is enacted through various forms of multilateral trade agreements; e.g. the General Agreement on Tariffs and Trade (GATT (World Trade Organization, 1994)), The World Trade Organization (WTO), the North America Free Trade Agreement (NAFTA), and the European Union (EU). However, in reality, it is very difficult to remove trade barriers because a country's trade policy gives the priority to the national interest or benefit. Trade barriers include tariffs to imports, import quotas, taxes, or subsidies to exports and non-tariff barriers (e.g. regulatory legislation).

The classical theory of international trade claims that the trade occurs because of the different characteristics of each country's trade conditions; e.g. difference in labor productivity (Ricardian comparative advantage) and in resource endowments (Heckscher-Ohlin model). However, this approach has limitation to explain the current pattern of trade; e.g. intra-industry trade with differentiated products between countries that have a similar level of development (Kurgman, 2008).

In the 1970s, **new trade theory** appeared with an amplified explanation of the current trade features (Krugman, 1979; Helpman & Krugman, 1985; Grossman & Helpman, 1993). The new trade theory, which combines international trade theory with industrial organization theory, explains that the international trade patterns are determined by the industrial characteristics.

The classical economic analysis was mainly based on the assumption of perfect competition; however, this is limited to explain the real market situation (e.g. oligopolistic competition). New trade theory is based on internal economies of scale (increasing return) and monopolistic competition (Chamberlain, 1933; Dixit & Stiglitz, 1977). The international trade allows the market expanding effect; the variety of products as well as the scale effect. Unlike the classical trade thought, new trade theory recognizes government's strategic actions to pursue excess profits under imperfect competition (e.g., oligopolistic market) because international trade is seen as an extension of the domestic market. The international competition occurs to gain excess profits based on economies of scale or R&D externalities.

1.3 Strategic trade policy

Strategic trade policy is based on new trade theory; it is a form of governmental industrial policy that aims at improving a country's economic performance by promoting specific exports or discouraging certain imports. The aim of such policy is to improve the domestic welfare by shifting profits from foreign markets to domestic firms. The policy includes various measures such as export subsidies, taxes, and import tariffs, industrial standards, grants, or low interest loans, etc. Government's interventions discourage foreign firms to enter in the profitable market**;** Spencer & Brander studied roles of export subsidies in the international competition (Spencer & Brander, 1983; Brander & Spencer, 1985). Such government's strategic actions change the rules of game enabling the influx of excessive profits into the domestic market.

Strategic trade policy was started in the US to protect the domestic market against Japanese firms that encroached automotive and electronic industries in the 1980s. Strategic trade policy is often applies in high-tech industries that require a large capital investment (e.g. aircraft) to create the first mover's advantage.

The government's strategic intervention establishes barriers to entry into markets to protect the domestic industry. There are many cases observed in the history; Europe's Airbus vs. the US Boeing (Krugman, 1987) and Asian (South Korea, Japan) semiconductor industry. However, strategic interventions by more than one government can lead to a Prisoner's Dilemma; trade agreements that restrict such interventions can be a solution to avoid such situation.

Our study is based on strategic trade theory (Paul R. Krugman, 1987). It demonstrates how the government's strategic trade policy led to an economic damage to actors in the complex global PV market.

2 PV globalization effects on the national PV policy mechanisms

In this section, we analyze how PV globalization (external factors) gives impacts on a country's complex and dynamic PV policy mechanisms. We have identified issues related to the interaction of different countries' policies as critical problematics in the complex PV policy mechanisms in Part II. We now take a closer look at change in German policy mechanisms with Chinese entry in the global PV market. Chinese inputs in the global PV market have enhanced the globalization of PV market. We compare the change in German policy mechanisms and interactional trade effects before and after the massive entry of Chinese products in the German market.

2.1 PV supply-demand policy mechanisms in Germany

It is important to understand how the German PV policy mechanisms worked before; it helps better differentiate benefits or damages from the external factor' intervention in the German national PV policy mechanisms. Prior to China's dominance in the PV market, Germany had been playing an important role in the global PV market for both supply and demand side. As seen, however, its share was absorbed by the Chinese with the globalization of the PV market. Here below, the German supply-demand mechanisms with policy supports are presented before the Chinese entry; this gives a basis to review globalization and trade effects.

It was defined that FIT system was one of the major drivers used to develop the PV market in Germany as early as 2000. The German PV policies aimed for combined effects of the demand-pull strategies (e.g. FIT system) and technology-push with R&D and financial incentives for production (e.g. low-interest loans).

Figure 77 demonstrates the German policy support mechanisms assuming linear demand and supply curves to simplify our explanation of the policy change pathway. Q refers to installed (sold) quantity on X-axis, and P refers to the PV system price on the Y-axis.

The German FIT system was planned based on a long-term vision (a 20-year contract). It is a foreseeable mechanism, which makes it possible to adjust the tariffs according to PV market development, applying a progressive reduction in the tariffs (Federal ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), 2007). In 2000, under the EEG, Germany decided to create a market by stimulating the increase in installation demand with the FIT support; as shown below, the demand curve shifts upward (D to D0). The new demand curve and the supply curve met at E0, attracting new investments in the PV market. The shift range can differ from one year to another year according to the policy decision; for example, under the amended EEG, new rates of the FIT support were rolled out in 2004 and in 2009 (Deutsche Bank Group, DB Climate Change Advisors, 2011).

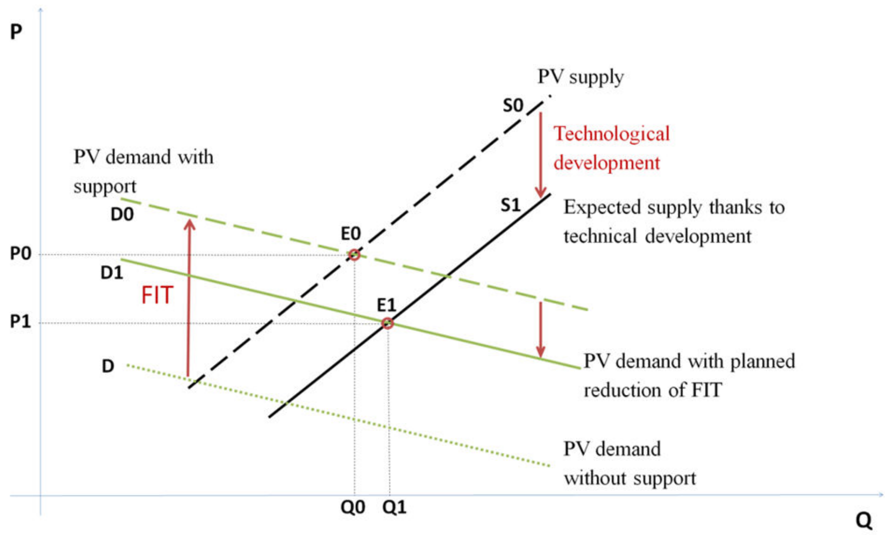


Figure 77: German policy support mechanisms

Next, the main phenomenon of the demand curve shift from D0 to D1 began from 2004. Under the amended EEG, the government set the decreased FIT rates. The reduction degree changed several times; e.g. a fixed reduction from 5% to 6.5% was applied every year between 2004 and 2008. A corridor digression system was implemented in 2009 with a reduction range from 5.5% to 7.5%, which was once again revised for the further reduction in 2011 (Deutsche Bank Group, Op. cit.).

The price reduction was planned based on condition that the PV industry gains the competitiveness by reducing production costs through technology progress driven by R&D activities and the accumulation of experience (IEA PVPS, 2005b). This means that The FIT price mechanism assumes that PV price reduces each year. This stimulated the supply curve shift from S0 to S1. The government policy designed to reach a new equilibrium at E1 actually set out to obtain results in terms of production cost reductions and installation growth.

As Figure 77 illustrates, the German policy strategy aimed for incremental improvements in production cost cutting and installation growth, with focus placed on the commercialization of silicon wafer-based solar cell (IEA PVPS, Op. cit.).

2.2 International trade effects before the mass entry of Chinese products

It is useful to review the German market equilibrium before the mass entry of Chinese products into the European market; it is because the German PV policy support mechanisms were designed based on this condition.

The global PV industry competition was weak until 2007 and largely dominated by two players, Germany and Japan, which gave them similar economic benefits. Both countries developed the PV industry covering the whole value chain based on its own national strategy plan (IEA PVPS Germany, 2002 to 2011; IEA PVPS Japan, 2002 to 2012). The situation changed, however, with fierce competition from the Chinese after the mass entry of their products from 2008, thereby provoking unexpected results.

Until China started its mass production from 2008, international trade was beneficial to the global PV market, supplying a larger quantity of solar cells and modules at a lower price compared with no-trade. To facilitate our explanation, we restrict the export-import mechanisms with Germany and Japan; these two countries were in the forefront of the global PV market prior to China's entry.

As seen, the German demand was never covered by domestic production; it imported solar cells and modules to some extent. Conversely, Japanese production had always exceeded their domestic need since 2002 and their production surplus was exported (see Part II chapter 2). Between 2000 and 2007, Japanese exports for the German market amounted for 3 billion US$ (UNCOMTRADE). Before the Chinese entry into the German market, imports were mainly from Japan (the top three importing partners in 2005: Japan 32%, China 16%, USA 9.6% (UNCOMTRADE)). Through this system, both importing (Germany) and exporting countries (Japan) gained economic benefits.

Figure 78 explains the benefits of the importing country with open trade. Under a no-trade configuration, the German market has equilibrium, E1, where the domestic supply and demand curves intersect with the market price, P1 with domestic outputs at Q1.

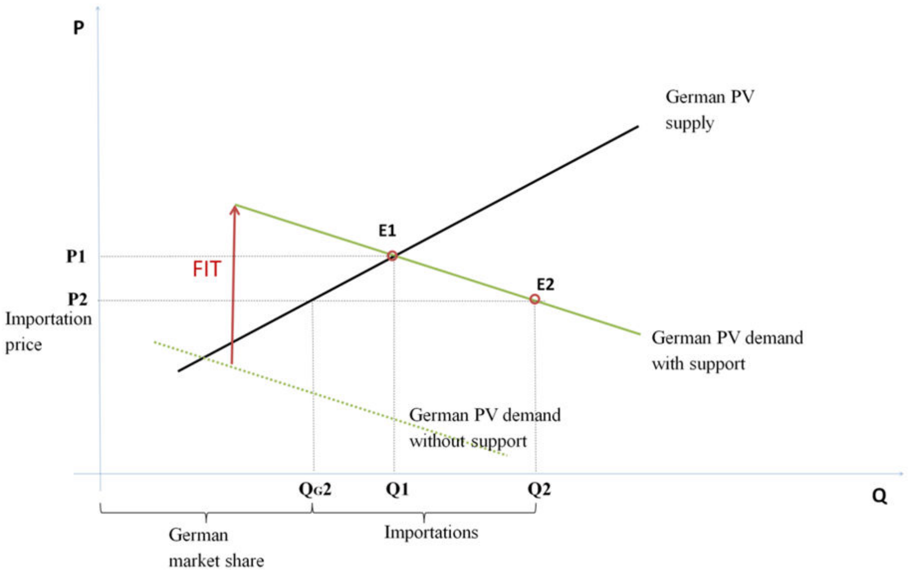


Figure 78 : Importation effects in the German market (before China)

With free trade, however, the supply increases, lowering the domestic market price to the level of the world price (P1 to P2). The German market has a new equilibrium E2 with market price, P2 and a supply quantity at Q2. The German production share is reduced to QG2 compared with Q1 under the self-supply system. However, the domestic supply for installations increased to Q2 with the import quantity being equivalent to the distance of Q2 to QG2 with the social surplus gain.

Moreover, the increase in the number of installations resulted in job creation (IRENA, 2011). The German policy design was based on these mechanisms, which have a relatively weak effect when faced with international fierce price competition; they allow economic benefits for both exporting and importing countries compared with the Chinese entry afterward. The German market gained benefits from open trade while pacing with the growing domestic installations. Before the start of fierce competition with China in 2008, the above-described mechanisms were applicable.

2.3 International trade effects after the mass entry of Chinese products

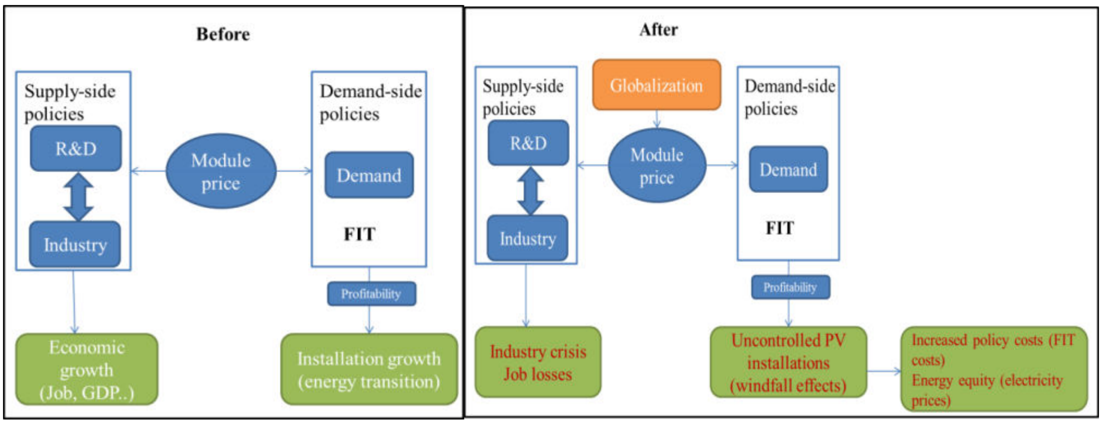


Figure 79: Changed German national PV policy mechanisms

As seen, the German PV policy mechanisms predicted an incremental price drop in module prices according to historical data and its expected technological evolution. However, the mechanism began to be threatened by the mass entry of Chinese products. Since 2006, China began to enter the

PV market with the government support. The globalized market with Chinese inputs added **unexpected external factor** in the German PV policy mechanisms.

China's dominance of the market was beneficial in terms of economies of scale through the increase in the market size with the mass production of solar cells and modules, which again lowered the global price of cells and modules from P2 to P3 (see **Figure 80**). This price level is much lower than the German government expected for the policy design, arising in some **unexpected consequences with the open trade system.**

Firstly, the German production quantity was reduced from QG2 to QG3, beaten by the competitive price offered by Chinese manufacturers (**market share loss**). China's decision to develop the solar PV sector as an economic growth engine through exportation onto the global market did reduce Germany's market shares. China immediately absorbed a considerable portion of the German market share faced with this fierce price competition. These phenomena are unexpected results for the German PV policy design. Germany recorded a €3.5 billion trade deficit in solar components with China during 2010 to 2012 (European Commission, 2014b).

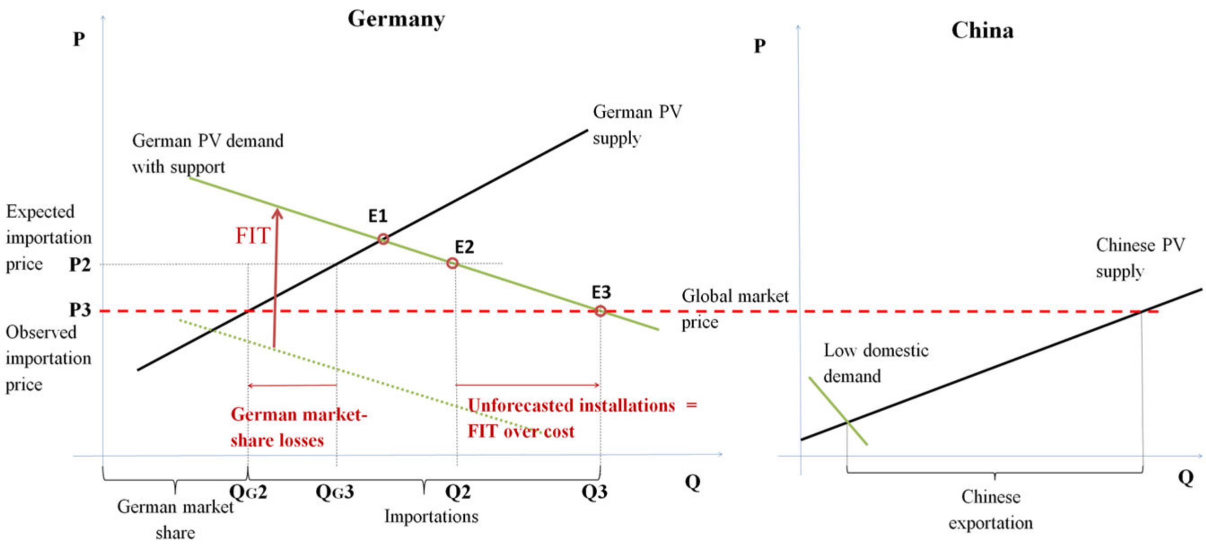


Figure 80 : Importation effects after China - consequences of the Chinese emergence in the German market

Secondly, with the mass inflow of cheap products into the German market, German installations rose much faster up to Q3 compared with the expected quantity at Q2 (**uncontrolled PV installation peak**). It was somewhat helped increase local installations based on cheap products at the very beginning. However, Germany installations rapidly increased to gain ***windfall profits*** and this became a financial burden for Germany, therefore inducing unpredicted FIT costs (**financial burden**). Local installers started to use cheaper components and this distorted the local FIT mechanism at the end (**speculation**), accordingly, some local key players closed down (**PV industry crisis**). Furthermore, as we have seen in the previous part, the increased costs of FIT system were financed by taxpayers through the energy bill; this largely increased household electricity prices in Germany, provoking **energy equity issue**.

The German policy decision on the expanded reduction of FIT (2009) (Deutsche Bank Group, DB Climate Change Advisors, 2011) did not bring the expected results which aimed at limiting uncontrolled installations in the German market. Rather, it led to fiercer competition in the global PV market, provoking Chinese producers to further reduce their production costs, pacing with the policy change in Germany, based on the expansion of large-scale production lines despite the global economic crisis. As a consequence, the German industry suffered from the reaction of the Chinese players and the global PV market encountered oversupply issues.

As China began to gain market dominance in Europe, China also encountered problems. It depends heavily on the overseas market to absorb its mass production. China is also dependent on imported silicon for its mass production due to technical barriers and policy strategies. In this context, the observed chain-reaction bankruptcies can be understood when the European market shrank due to its economic downturn. In addition, the Chinese government's decision to expand the domestic market can be seen as a natural result to resolve the national economic problem (Golden Sun program in 2009, a FIT scheme in 2011 (Zhang & He, 2013)). China needs to explore new avenues for market growth.

This analysis indicates **the importance of globalization based on trade effects with respect to PV policies.** The German market is more open to foreign products compared with the Japanese market, due to the general application of European policy and fewer institutional barriers (e.g. certification requirements and technical specifications in Japan). In this regard, the German market was more exposed to the global market, such as the world price reduction and foreign competitors' movements. This observed phenomenon provides a lesson for other countries in relation to their policy design and implementation to support PV development. Therefore, it is important to understand how a nation's PV policy mechanisms are influenced by external factor.

3 Strategic trade policy and the international competition

3.1 The global PV market characteristics

In order for us to explain how Chinese strategic trade movement changed the global PV market mechanisms, it is necessary to define the characteristics of the global PV market. The accurate comprehension of PV market characteristics is an essential step to analyze the influence of the external factors in the PV policy mechanisms. Therefore, here below, we demonstrate the global PV market features using the production capacity expansion game. And then, we explain how the situation of the global PV market changed.

3.1.1 PV production capacity expansion game

Before analyzing each player's strategy, it is important to define ***the characteristic of the global PV market.*** We consider the condition with production capacity expansion in order to include new player's entry in the existing PV market. The simplified game model of PV production capacity expansion is presented using the form of non-cooperative game (two competing firms independently determine business strategy to win market share)[162]. The basic elements of game are as below;

- ***Player***: a decision maker, we assume that there are two groups of firms in the global PV market
    - Enterprise 1 (E1) : Market leaders
    - Enterprise 2 (E2): Market followers
- ***Action:*** each player aims to maximize profits. They sell the homogenous product and compete with each other aiming to gain larger market shares in the global PV market.
    - Both have two choices: invest or not invest
- ***Payoffs***: the final returns to the players at the conclusion of the game.
    - There are four possible cases ((a,b), (c, 0), (0,d), (0,0)) in terms of expected profits of Enterprise 1 and 2, respectively. The enterprise, which decides not to invest, will have zero profits regardless of the other firm's decision.
- ***Equilibriums*** occur when all players in the market have no incentive to alter their behavior.

E1 / E2	*Invest*	*Not invest*
Invest	a, b	c, 0
Not invest	0, d	0, 0

Table CVII: Competing game (non-cooperative) through expansion of production capacity

There are three possible cases, which define different market characteristics. The assumptions are made based on expected payoffs.

(1) Assumption: a, b, c, d > 0

In this case, the market is big enough to accommodate all players with new capacity of production. The market continues to grow or is unsaturated.

Equilibrium: In this case, Nash equilibrium is achieved when both E1 and E2 decide to invest with the payoff (a, b). The decision to invest is dominant strategy[163] for both players. If E1 and E2 invest in building new production capacity and both produce, then the market will give positive profits to both players.

(2) Assumption: a, c, d > 0 and b < 0

This case refers to the market situation when there is the first-mover advantage or when the following firms are subordinate to the leading firms in terms of production capacity expansion.

Equilibrium: In this case, when the leading firm decides to invest, the follower will give up. If both E1 and E2 invest in expanding new capacity and both operate, then E2 will have the losses.

[162] Non-cooperative game: two competing firms independently determine a pricing or business strategy to win market shares.
[163] Dominant strategy: regardless of what any other players do, the strategy gives a larger payoff than any other strategies.

(3) Assumption: a, b < 0 and c, d > 0

In this case, the market is not big enough to absorb both firms. The market is almost saturated and it demonstrates a slow market growth. In this case, if both firms operate, then they will gain the losses because of excess supply.

Equilibrium: This market allows only one firm's profits. If E1 and E2 invest and both operate in the market, then E1 and E2 will have the negative profits. However, when one firm operates, the other firm had better not invest. There are two Nash equilibriums; when E1 invests, E2 gives up in expanding the production capacity and vice versa, the expected payoffs are (c,0) or (0,d).

3.1.2 The global PV market situation based on production capacity expansion game

Case of (1)

The PV market demonstrated a consistent market growth before the PV industry crisis since 2008. The European policy to simulate PV installations supported this market growth. Therefore, the PV market had balanced supply-demand mechanisms allowing expansion of new capacity of production. This case fits with the historical movements of PV market growth. Chinese policy decision was made based on the condition that this trend of global PV market continues.

Case of (2)

The first mover's advantage does not count a lot in the dominant crystalline silicon-based PV production, especially in terms of labor-intensive PV cell and module manufacturing (Mehta, 2011). The downstream manufacturing of crystalline silicon-based technologies has low barriers to entry because the process is simple and cost-effective. It is subject to substantial economies of scale. Furthermore, technology transfer and knowledge spillovers through multinational firms' activities are common practices (de La Tour, et al., 2011). The PV market has gained knowledge spillovers from other technologies, regions, firms (Nemet, 2012). The first-mover advantage is feasible when a firm has a unique technological leadership for specific technologies. This situation can be possible with PV technological breakthroughs. In this regard, the second case of market feature does not fit with the current global market situation, which is dominated by crystalline silicon-based PV production.

Case of (3)

The PV market mechanisms have changed with the economic downturn in 2008, which sharply reduced European PV demand. The market's limited demand became a barrier for new expansion of production capacity; the stagnant market could not absorb the increase of production capacity. Besides, to make things worse, during 2008 and 2009, the expansion of production capacity rapidly increased with Chinese inputs in the global PV market, leading to the excessive production. The fierce cost reduction competition was intensified with the global oversupply situation. From here, we can conclude that the shrinking market growth faced with the global recession, the solar PV market situation turned to the third case, which only allows a few firms' profits. If both invest, they will have negative profits (see Part II chapter 3).

3.2 Chinese strategic trade movements

In this section, the feature of external factors is explained to understand the dynamics of PV policy mechanisms. A game theoretic approach was used to investigate Chinese policy decision with strategic movements and the influence on investment choices and payoffs. Chinese strategic movements are explained using *strategic trade policy.* Why Chinese PV firms largely expanded their production capacity despite the shrinking demand growth? The ulterior motive is identified based on the analysis.

3.2.1 *Chinese investment choice and payoffs without government's policy support*

The situation is illustrated in a duopoly setting. Both are considering an investment in adding new production capacities to reduce production cost per unit. As seen, the PV market benefits from the substantial economies of scale. Some firms with mass production capacity will gain better economic competitive having decreased production cost per unit. The PV industry requires a high cost for initial investment. Each firm will be affected by its competitor's decision.

- ***Player***: We assumed that there are two payers: German producers and Chinese producers.
- ***Action (strategy):*** Each player aims to maximize profits. They sell the homogenous product and compete with each other aiming to gain larger market shares in the global PV market.
- ***Payoffs***: The final returns to the players at the conclusion of the game.
- ***Equilibriums*** occur when all players in the market have no incentive to alter their behavior.

Chinese producers / German producers	*Produce*	*Not produce*
Produce	a, b	c, 0
Not produce	0, d	0, 0

Table CVIII: Payoff matrix without policy support

1) **Assumption: a, b< 0, and c, d >0** (cf. 3.1.)

The market is not big enough to accommodate two players with new capacity of production.

Equilibrium: When German players invest, Chinese players give up in expanding the production capacity and vice versa, the expected payoffs are (c,0) or (0,d).

The possible outcomes of the game are presented by the payoff matrix in Table CVIII. Both German and Chinese firms are considering expanding their production capacity to gain the economic competitiveness of production to take the leading position in the global PV market. As seen, however, the market is not profitable enough to embrace two companies (see Part II chapter 3). Both firms have a binary choice; produce or not produce. If German and Chinese firms decide to produce, both will make a negative profit of *a* and *b* respectively. When German firms produce and Chinese firms do not, German firms will earn *c,* Chinese firms will earn zero and vice versa. What strategy should each firm choose under this payoff mechanism?

If German first starts the production with the market leading position, *the upper right hand corner of payoff matrix* is the outcomes of the game. Germany had the market power in the global PV market since early 2000s; it accounted for 22% of the world market share in 2007. **Chinese will not produce to avoid negative profits and German firms will gain the profit of *c*.**

3.2.2 Chinese investment choice and payoffs <u>with</u> government's policy support (strategic trade policy)

We now consider a different scenario; Chinese government decided to commit to the PV industry growth by giving industry policy support of *s*. Can this change the outcomes of this game? This case can be interpreted with the application of the *strategic trade policy theory.* Different payoff matrix with policy support is developed based on Krugman's strategic trade model (Krugman, 1986; Krugman, 1987).This new setting gives new equilibrium and different investment choices from Table CIX. It is important to justify the additional gain of *s* for Chinese firms because they changed Chinese investment choices.

Chinese producers / German producers	*Produce*	*Not produce*
Produce	a, (b+s)	c, 0
Not produce	0, (d+s)	0, 0

Table CIX: Payoff matrix with policy support (based on strategic trade theory)

Chinese government strategic policy support (justification of s)

In this part, we demonstrate Chinese government's intervention aiming to give policy support of *s*. Chinese governmental industrial PV policy aimed to improve the PV industry's competitiveness to gain the global market share. There are many evidences that Chinese PV industry was supported by the governmental various forms of subsides. The Chinese government, at both central and local levels, supported PV manufacturing investment through various forms of subsidies; innovation funds, regional investment support policies (2009) issued by some Chinese city governments, as well as free or low-cost loans, tax rebates, research grants, cheap land, energy subsidies and easy credit, and technological, infrastructure and personnel support (Gang, 2015). China's low labor cost and low energy price facilitated the industry's expansion by reducing production costs (Grau, et al., 2012).

Chinese subsidized credit supported PV producers for capacity expansion regardless of their productivity levels, even if some of these loans may face high risk of default. To give an example, between 2005 and 2012, Wuxi Suntech Power Co. Ltd, once China's largest PV manufacturer, was able to receive a loan up to US$ 3.7 billion; it was mainly due to a municipal government mandate on local state-owned banks for providing low-interest loans to Suntech (CHEN GANG 2015). Furthermore, from 2006 to 2011, Wuxi Suntech also received tax rebates and other forms of refund amounting to 8.65 billion yuan (about US$ 1.42 billion) from the government with the aim of promoting exports.

Moreover, faced with strong global competition after 2009, despite the world over production situation, China government did not stop providing subsidies in PV solar industry to protect local GDP and employment. China's continuous easy access to credit and permissive standards gave advantage for local manufacturers to gain scale effects for building gigawatt (GW)-scale plants (Goodrich, et al., 2011).

Given this condition of Chinese government supports to PV industry, how differently will the Chinese PV industry respond? The new outcomes of the game are presented in Table CIX. **The Chinese firms will have additional gains from subsidies of *s*.**

New equilibrium and investment choice <u>with policy supports of s</u>: Chinese supply-side policy objective

1) **Assumption: a< 0, (b+s)>0**

   Supported by government policy support of *s,* Chinese firms will gain positive outcomes regardless of the German firm's strategy. This assumption was the basis of Chinese export-oriented policy strategy. The aim was to give industry support to gain the global market shares based on the price competitiveness.

- **Equilibrium:** Chinese players will invest in all cases and this will drive the German players to move out of the market. The expected payoffs are (0, d+s).

Chinese firms will move differently with a new payoff mechanism. Chinese firms will make positive profits regardless of what German firms do because policy support covers the expected negative profits of Chinese firms when both produce. On the other hand, German firms know that Chinese firms will produce in either case.

As seen, the current PV market does not allow absorbing both firms because of the decrease of the global demand growth. When German firms produce, they will gain negative profit of *a*. However, they will gain zero profit when they do not produce. Not produce than produce does less harm to German firms; the equilibrium of this game can be found *in the lower left-hand side corner*.

In fact, as seen, supported by governmental aids, many Chinese PV firms have invested in expanding new production capacities to gain the economies of scale; there was a massive entry of new players into the PV market during the late 2000s. As seen, strategic trade policy demonstrates how the profit transfers from one country to another. Trade surplus in solar components and equipment was somehow shifted from Germany to China. Consequently, Chinese firms took a share of the market away from their competitors based on an export-oriented strategy and finally surpassed their German and Japanese competitors since 2007, occupying a dominant market share (58% in 2012 for cell production (IEA PVPS, 2002 to 2013)[164]) in the global PV market.

Excessive production in the global PV market and negative payoffs: dynamic results

However, the strategic policy theory has limits to explain the dynamic feature of market structure and potential response (Dixit & Kyle, 1985). There are several issues to be discussed to better explain the actual payoffs.

[164] Authors' calculation based on IEA PV PS data.

- **Market risks**: Chinese strategic movements were heavily dependent on the overseas market which is difficult to control. Moreover, the PV market is highly subsidized, thus very volatile according to policy decision.
- **Dynamic changes of market structure:** the decreased demand growth in Europe faced with the global economic recession.
- **Retaliation between countries**: trade disputes were rolled out.

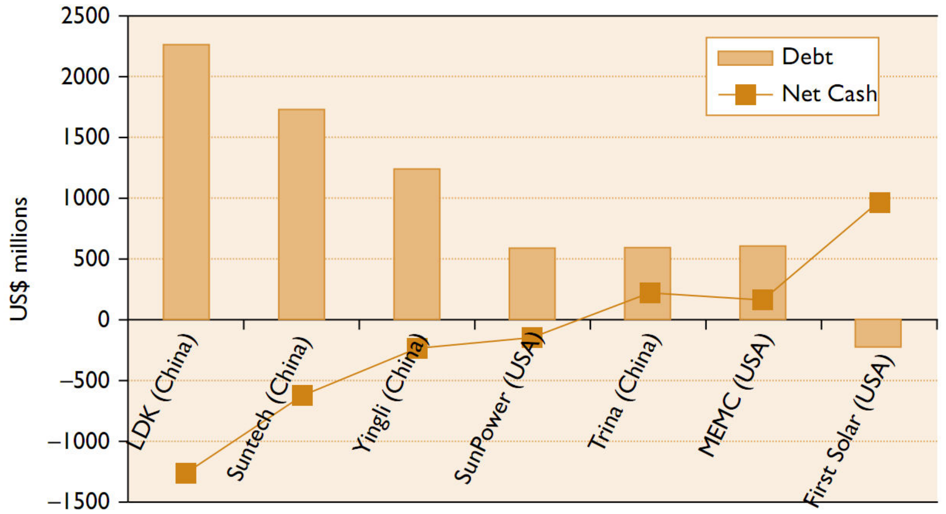
Chinese firms' investment decisions to enter the PV market are based on the combination of the government policy support to promote the PV industry (e.g. access to capital) and the strong market signal in Europe under the political willingness to stimulate PV installations. However, Chinese export-oriented policy strategy contained high market risks. China's expansion of production capacity was heavily export-oriented without establishing a domestic market. For example, China exported 97.5% of its modules produced in 2006 and 96% in 2009 (IEA PVPS, 2010b). Therefore, Chinese strategic trade movements without domestic market development included high market risks.

In addition, the PV market is very dynamic. The prompt response to the rapidly changing market situation is essential to avoid economic damages in the international market. The strong market signal of PV growth in Europe suddenly changed because of the reduced demand growth faced with reduced policy support caused by the global economic recession. This provoked a change in the context of PV policy system. Chinese supply-side policy was designed based on the observed trend of market growth. However, even though the characteristics of PV market were modified with the context change, the country maintained the decision that was made in different policy context. Therefore, the industrial competition in the global market continued due to the inertia of policy implementation and time lag in market response.

Both continued to support its production since PV industry is a strategic industrial position in both countries (see Part II). In particular, despite the stagnated global market, Chinese firms continued to expand their production capacities to gain economies of scale; this decision led to overproduction issue in the global market. As seen, before the mass entry of Chinese products, the global supply and demand almost matched. However, Chinese production capacity alone represented almost 2 times of European demand in 2012.

Furthermore, the strategic trade policy can provoke retaliation (trade dispute or trade war) between countries. China faced obstacles for imports of PV products going through trade disputes with the U.S. and EU. In 2012, the U.S. decided to impose duties of as much as 250% on Chinese PV modules to protect the U.S. manufacturers. The EC (European Commission) also decided to impose provisional anti-dumping duties (average 47.6%) on imports of solar panels and key components (e.g. cells and wafers) from China (European Commission MEMO, June 2013). As a consequence, Chinese firms started to delocalize the production lines to Taiwan and Malaysia. In addition, this decision caused trade retaliation; China also imposed anti-dumping duties on US polysilicon as much as 57% on solar-grade polysilicon from the U.S. (PV magazine, 2013).

The results of Chinese strategic trade policy were observed in process of time. The fierce global competition provoked negative payoffs to both countries. In the previous section, we have seen Germany's negative payoffs influenced by Chinese strategic movement (section 2). However, China also encountered negative payoffs with a time lag. Proofs were observed in various aspects: bankruptcy of PV firms and job losses in China (see Part II). Many Chinese PV firms experienced financial losses.



Source: Compiled from Brean Murray, Carret & Co. estimates, independent research.

Figure 81: Debt & net cash balance of Chinese and U.S. companies, Q4 2010 (Haley & Schuler, 2011)

China somehow failed to meet the intended policy objectives; this raises a question about the efficiency of Chinese industry policy support in the long-term. In addition, it should be examined how China allotted money for subsidies.

In conclusion, in this game setting, both German and Chinese firms gained negative payoffs at the end. The complexity and dynamic features of the global PV system largely influenced them. Furthermore, Chinese strategic trade policy provokes trade disputes with trading partners. It is important to notice that this situation would again change the policy context of Chinese supply-side policy by further reducing the size of potential market. Taken all these situations into account, the losses of Chinese firms can be increased in the future.

3.3 New game setting: market expansion game

We have seen how the non-cooperative game driven by Chinese strategic trade movement caused negative payoffs for both players. The global PV market is suffering from the oversupply issue, PV industry crisis and long-lasting trade disputes.

We consider new game setting here below to change the market characteristics. Both countries now want to exit the current market situation through new market development. We suppose that both countries' strategic decisions are to increase demand rather than staying with a limited market size. The aim is to grow the size of pie in the global PV sector; the shift of market characteristics from case 3 to case 1 (see section 3.1).

There are two choices: *not expand* (stay with the current business patterns) or *expand* (invest in new market or business). The development of new market (*expand)* gives the growth opportunities to both players with increased profits. If they decide to continue the PV business as the way they do until now (*stay*), they gain zero profits from the new market.

E1 / E2	*Expand*	*Not expand*
Expand	a, b	c, 0
Not expand	0, d	0, 0

(1) Assumption: a, b, c, d > 0

In this case, the market is big enough to accommodate all players. All players receive positives payoffs to their investment.

Equilibrium: Nash equilibrium with the payoff (a, b).

(2) **Assumption: a, c, d > 0 and b < 0**

This case concerns a special market with first-mover advantage and high entry barriers like exclusive technology expertise.

Equilibrium: When the leading firm decides to invest, the follower will give up.

(3) Assumption: a, b < 0 and c, d > 0

This market is not big to guarantee for all players. In this case, if both firms operate, then they will gain the losses because of excess supply.

Equilibrium: Two Nash equilibriums; (c, 0) or (0, d).

There are three possible cases in terms of payoffs of the market expansion game.

<u>Case of (1)</u>

PV market can be developed in regions without PV business (e.g. electrification of the developing countries). Under this case, the development of new markets gives growth engines to both countries' PV industry. However, to make assumed positive payoffs feasible, a risk analysis should be conducted to mitigate any potential risks that can be occurred (see Part I chapter 4). The payoff matrix can be changed faced with market dynamics.

<u>Case of (2)</u>

This can be feasible with technological breakthroughs or innovations in usages; e.g. non-crystalline or hybrid technologies, coupling with other sector like green buildings, electric vehicles or H_2. The first-movers who successfully gain such competitiveness will earn big profits.

Case of (3)

This market is closely linked with the fierce international competition supported by strategic trade policy. When new markets or new business opportunities are created, the global competition can be again increased based on strategic trade policy to gain the market share. The same mechanisms can be rolled out in the global PV market. To justify this, we can refer to the current oversupply issue in the global polysilicon market. Once Chinese PV industry successfully expanded their production capacity in modules, China's strategic movement was extended in polysilicon market. With Chinese inputs in the global polysilicon market, the global market encountered the overproduction problem. The current selling price is around 12-15$/kg (PVinsights, 2016), which is estimated less than the manufacturing costs (~15$/kg) (Insight Semicon, 2016). Similar mechanisms were rolled out in the global polysilicon market followed by overproduction of solar PV module market. In conclusion, new market expansion can probably give positive payoffs in the short-term; however, it is hardly guarantee the long-term positive payoffs.

How those countries can be better off in the global PV market?

When the game is played repeatedly, both players can behave differently to maximize the profit. They can change strategy over time in response to the competitor's behavior, market change and lessons from the past.

As seen, as a consequence of strategic trade policy, the established production capacity largely exceeds the global demand increase. However, the long-lasting trade disputes reduced the scope of business market of the relevant industry players. The global PV industry needs to find a new strategy. Both countries want to exit from the current industry crisis with positive payoffs from the market expansion decision. However, PV firms, in particular Chinese firms, might be reluctant to make new investment because of the current situation with financial losses unless the investment is subsidized. If both decide to stay with the current business, the presented negative payoffs will remain the same. In addition, it is possible to consider entering the market once a market is formed by the other player. However, this time, trade barriers can be designed from the beginning of the market development to protect the new market from the competitors. Therefore, both have interested in reacting differently to avoid the reproduction of the same mechanism of PV industry crisis.

There are three possible cases in terms of investment decisions.

Cases		Costs	Returns
Business-as-usual (BAU) baseline case		Sunk costs	Negative profits (Excessive production , trade disputes)
Expand (new markets)	alone	High investment costs	Full profits/losses from new markets (New outlets for the overproduction)
	together	Reduced investment costs	Shared profits/losses from new markets (New outlets for the overproduction)

Table CX: Possible cases in terms of new market development

Cooperative actions can be an option if they lead to better outcomes for each player than the business-as-usual (BAU) baseline case or alternative option (e.g. sole investment). As seen, both have negative profits under the BAU case with long-lasting trade disputes and excessive production. Firm's previous investment is referred to sunk costs (they have already been made and cannot be recovered). In economics, sunk costs should not be considered to make rational investment decisions. Furthermore, the demand-side policies in Europe are more cautious gone through the expensive experience with FIT system and the demand growth in Europe slowed down. The new demand creation is needed. However, as seen, the financial situation is not the same as before the PV industry crisis. Given the current circumstance with financial difficulties, the sole investment with high risks seems difficult to make for both players even though it is more attractive option with higher returns. If they develop new markets together, the total costs can be shared with less business risks. The second best plan (invest together) seems more realistic option for both with less investment risks.

However, they act to maximize their own profits. There is no guarantee that both will cooperate. With the dynamic features of market, the cooperation without enforceable binging agreements is rarely reliable. They can break the promise of cooperation anytime to increase their payoffs. Both need a reliable commitment to make sure the other party will be cooperative for the future game. If any player has incentives to break the cooperation, it is not stable solution.

How can we transform this situation to a stable solution? One good solution is that players can consider joint investment strategy (e.g. strategic alliance, joint venture) to create new markets. Public policies have an important role in supporting this movement by removing institutional risks or context risks. Cooperative actions can be possible on the condition that Chinese strategic trade policy is stopped. In addition, international governance also has a key role in negotiations. The targeted areas should be where neither firm would have enough knowledge to succeed on its own to attain the perfect cooperation game. In order to divide profits from their joint investment, the good strategy for both firms is to find complementary mix.

4 Conclusions

This chapter presented a sharp insight into complexity of PV policy system in the international context. We provided an in-depth analysis to explain the dynamic features of PV policy mechanisms combined with globalization. The global market balance was broken as a result of interactions of different policy strategies under the globalization.

We demonstrated how German policy was influenced by Chinese strategic trade policy under the non-cooperative game setting. Chinese strategic trade movement changed the German policy mechanisms producing unexpected results in terms of domestic installations, PV industry, jobs, PV policy costs as well as international trade. Those complex interactions of Chinese supply-side policy and German demand-side policy are analyzed using strategic trade theory and international trade theory. It was demonstrated how the non-cooperative game setting ended with losses for both players.

The global PV market suffers from the oversupply issue, PV industry crisis and long-lasting trade disputes. The long-lasting trade disputes reduced the market size for the relevant industry players.

In this regard, we also considered a new game setting to provide the possibility of demand creation. Since the global PV business is not one time game, both parties can behave differently to maximize the profit. They can change strategy over time in response to the competitor's behavior, market change and lessons from the past. In order to avoid the current negative payoffs with overproduction and long-lasting trade disputes, both players have interests to look for new business opportunities. The development of new market can bring new outlets for the oversupply of PV products and business opportunities to both players. Taken the financial difficulties of PV firms into account, the cost-sharing through cooperative actions seems a realistic option to develop new market. However, in order to make this a stable solution, public policies have an important role in preparing an appropriate policy framework and creating business climate for the new market development in the international context.

Chapter 3. PV development opportunities with international cooperation

In this chapter, we intend to propose strategic directions to solve the oversupply issue based on international cooperation. The goal is to suggest further growth opportunities of PV power in the international context. First, we propose to develop new PV markets in less-developed and developing countries with little access to electricity. We quantify those growth opportunities and the contribution to the global PV sector. And then, we also propose other possibilities of cooperative political actions to enhance the PV system competitiveness.

This study is conducted in three steps. First, we present possible solutions to escape the current industrial crisis with overproduction. We then propose a solar PV electrification program in the developing countries (section 2). This aims to give new outlets for the oversupplied PV market. Apart from this objective, our study attempts to demonstrate other benefits of this option; e.g. a solution for the world energy poverty problem, reduction of global CO_2 emissions, and contribution to enhance PV competitiveness. In addition, using the learning curve theory, we propose a smart strategy (we name it 'PV domino diffusion strategy model') to maximize the cost reduction effects benefiting from the market expansion. Next, we also suggest other cooperative political actions to enhance the PV system competitiveness in non-module sector (section 3).

1 International cooperation for future PV growth

1.1 New market equilibriums

In order to prepare new international PV global setting for the future PV growth, the unbalanced PV market mechanism should be first solved with new equilibriums. Those approaches had better conduct in the international context because the PV market is now largely globalized.

The global market oversupply problem can be solved through a supply decrease by restructuring of the global manufacturing system or expansion of the market in search of new market equilibriums. The decrease of supply-side seems a limited solution since heavy investment has already been made to build many large-scale GW plants in the global PV market. In addition, an innovative approach can intervene to propose new usages (e.g. coupling with other technologies such as mobility, storage and building). Innovation in sectors related to PV policy mechanisms is also important to further enhance the PV competitiveness. Thus, opportunities can be examined to explore new outlets of solar PV growth:

- **Supply-side responses**: restructure the supply system (e.g. mergers and acquisitions, new government-driven strategies)
- **Demand-side responses**: explore new markets such as less-developed countries with less access to electricity
- **Innovation approach**: add value through new usages by coupling with other sectors (mobility, buildings, smart grids, and storage) or bring innovation for technological breakthrough or cost reduction.

On this last point, the development of other PV technologies (e.g. thin film, hybrid, concentration PV, organic PV, etc.) is an important issue to find new markets. Some specific policies could be applied (e.g. niche market development or specific support) to counterbalance strong crystalline silicon competition due to scale effects that lock the PV market to other interesting but less commercially mature technologies (technological lock-in (Finon, 2008)).

1.2 International cooperation for a sustainable growth

It is worth considering benefits related to solar PV expansion in other regions such as the developing countries or less-developed countries. This implementation of solar PV (on both supply- and demand-sides) in those regions can be interesting for existing players as well as new entrants.

It can provide an opportunity to create new outlets for the excessive production capacity or business for existing players. At the same time, new regions can obtain an optimal system with economic development in addition to the new energy solution to address the energy equity problem. This can be explained based on the green growth theory (Jouvet & de Perthuis, 2012; Lee, 2010; 2011) (see Part I).

The PV system can be used to solve the electricity problem in the world because it can be easily decentralized and the economics of PV system has been largely improved in recent years. At the same time, through the establishment of a new paradigm with sustainable energy supply through PV system and power consumption, the new region can have another development route with a more sustainable Environment Kuznets Curve (EKC) (Kang & Lee, 2009, p. 47; Stern, 2004).

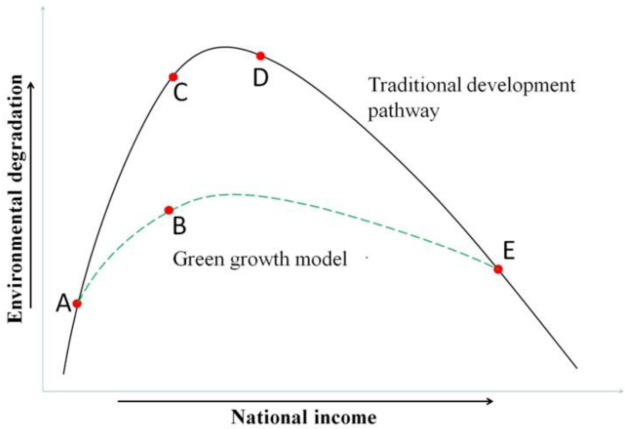


Figure 82: Possible international cooperation - an economic model of green growth

This concept can raise concerns since it broadens economic gaps between developed countries and developing economies when they do not have proper infrastructures and technologies to implement green initiatives. For this matter, however, coupling the international partnership of supply and demand can be recommended when looking for synergies. The accumulated experiences and knowledge in PV production and installation in the past can be passed down to new regions. It can also provide economic growth engines in this region. Therefore, it eventually allows those countries to attain economic goals through green mechanisms and the world environmental curve will fall with the expansion of sustainable energy systems across the world.

1.3 Possibilities of strategic cooperation

The current market is suffering from the fierce price competition leading to oversupply problem, this phenomenon was extended to the polysilicon market. In addition, the long-lasting trade disputes narrowed the scope of market for China, EU and the U.S. Therefore, those countries have common interest in developing new market to solve such problems. In the previous chapter, we have seen that cooperative actions open up possibilities to reduce investment risks through cost-sharing. We now present possible approaches in terms of cooperative actions.

Strategic alliances

The strategic alliances occur when two or more organizations work together to pursue mutual benefits under the shared objectives. Each party contributes in one or more strategic areas of the alliance (specific resources or skills) to achieve common goals. We can consider a complementary strategic mix between China and Germany to develop new markets in less-developed and developing countries. Complementary strategic alliances are established to take advantage of market opportunities and to create new value by combining partners' assets in a complementary way (Harrison, et al., 2001). For example, we can consider a vertical complementary strategic alliance to use their assets in different stages of the value chain.

Both have a complementary mix to create added value around the PV value chain (see **Figure 83**). Germany can contribute in terms of its competency area like silicon refining, equipment, machines for plants and engineering. China can supply cheap modules to new markets based on already established production capacity.

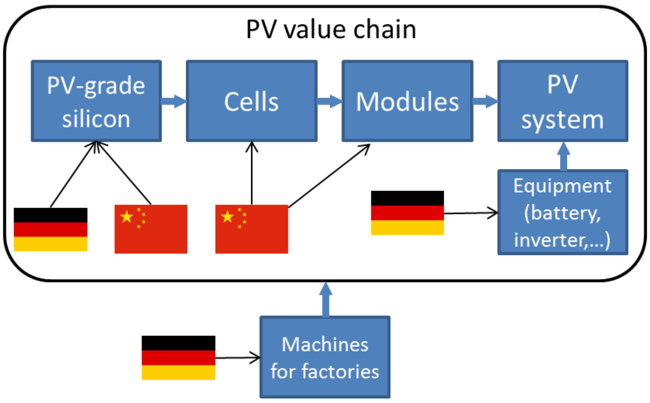


Figure 83: Complementarity of Germany and China in the PV value chain

Table CXI shows a summary of contribution, benefits and common interests from the strategic mix. It is interesting to focus on benefits of the global community. This can reduce CO_2 emissions by replacing the potential alternative (diesel generators) and solve the world electricity problem. Furthermore, it gives a sustainable development model in those areas. In addition, the advanced standards of technologies or PV installations can be transferred in those regions. This also includes standards of PV installations, related norms and technical specifications. The enlarged global market size will contribute to improve the competitiveness of PV power through experience curve effects. Quantified opportunities and effects are presented in the next section.

	Germany	China	New regions
Contributions	- PV-grade silicon supply - Engineering - Equipment - Expertise of PV installations and system management	- Cheap supply of solar cell/ modules - Expertise of PV manufacturing	- Favorable climate condition - Provide new business opportunities
Benefits	- New outlets for oversupply - Stable market for polysilicon & associated industry - Economic benefits	- New outlets for oversupply - Stable supply of silicon - Economic benefits	- Sustainable energy supply system - Economic development - Increase the access to energy
Common interests	- Reduction of CO_2 emissions (international objectives) - Solution for the global energy poverty problem (increase electrification rate) - Shift to a greener model for the socio-economic development of the globe - PV cost reduction through expanded market size and experiences		

Table CXI: Contributions and benefits from strategic cooperation

Risk analysis

However, as we have seen in Part I, the PV development contains various risks. Table CXII shows our risk analysis to develop such markets. Even though each risk will be different according to each country concerned, this analysis gives us a quick understanding of principal risks. The **financial risks** pose one of the great obstacles to develop PV markets in those areas. In addition, we can encounter **institutional risks** like lack of standards or lack of infrastructures. The **substitute risks** are important to consider in this region, they are closely related to the fossil fuel price change. Also, customers possibly prefer to use diesel generator rather than PV system because of the low cost of initial investment (**customer risks**). We need to prepare mitigation strategies to eliminate those risks prior to developing PV markets in those regions.

	Risks	Likelihood *	Notes	Strategies to reduce risks
Internal risks	Technology	1	Costs (e.g. PV system, battery)	Economies of scale
	Market	2	Preference to substitute (low investment costs)	Financial support Public education
	Institutional	3	Lacks of institutional framework, public training	Increase weak institutional area and trainings Adaption strategy
	Financial	3	Costs of capital, lack of access to capital	International climate fund Develop customized financing model
External risks	Supply	1	Overproduction of polysilicon	
	Context	2	Fossil fuel price change Economic situation	Carbon taxes

*Likelihood: 1 (low), 2 (medium), 3 (high)

Table CXII: Risk analysis in terms of PV market development in less-developed and developing countries

2 A case study on international demand creation for PV electricity

As suggested, a solution to solve oversupply in the global PV market can be sought in pursuit of new demand. This section aims to present opportunities of international demand creation based on a case study on the PV electrification in less-developed and developing countries. We have selected 49 countries, which have little access to electricity but abundant solar energy resources (see annex). Our analysis quantifies the size of potential market and the economics of PV power in these regions. It also accelerates the regional development by increasing access to electricity through low carbon economic development trajectories. Therefore, we also examine impacts on CO_2 emissions reduction.

2.1 Characteristics of selected countries

2.1.1 Electrification rate and potential solar energy output

Approximately 1.3 billion people lack access to electricity around the world. According to the World Bank, the energy access problems are concentrated in Africa and the Southeast Asia; however there are also significant solar energy resources in these regions (see **Figure 84** and **Figure 85**). It is thus possible to meet the electricity demand in these areas using the abundant solar energy resources.

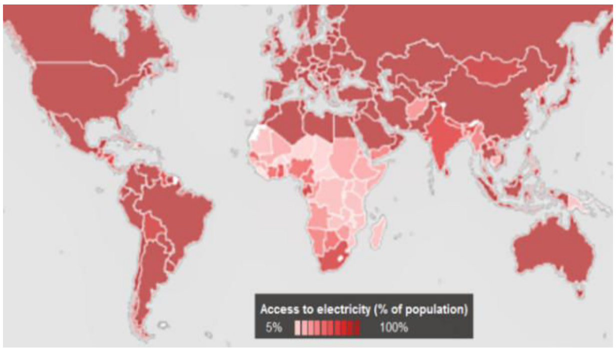


Figure 84: Access to electricity in the world (World Bank)

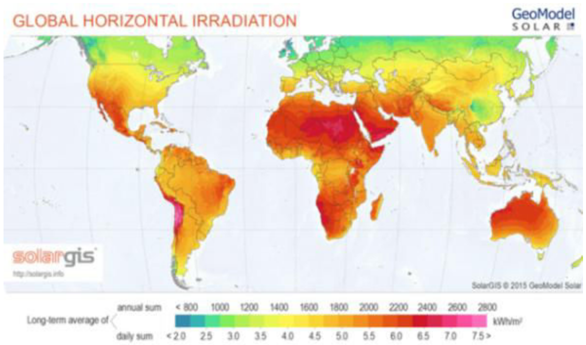


Figure 85: Global Horizontal Irradiation (GHI) in the world (SolarGis)

Our study is based on data concerning 49 countries in energy poverty regions with good solar resources, including the least developed countries in Africa, Southeast Asia, India and Bangladesh. They represent **1.06 billion people** (World Bank database). **Figure 86** shows the population percentage with access to electricity (in blue) and the potential output of PV power per year (in red, kWh/kWp/year) in these countries. The average potential PV power output is **1548 kWh/kWp/year;** this is about 50% higher than the average PV resources in Europe.

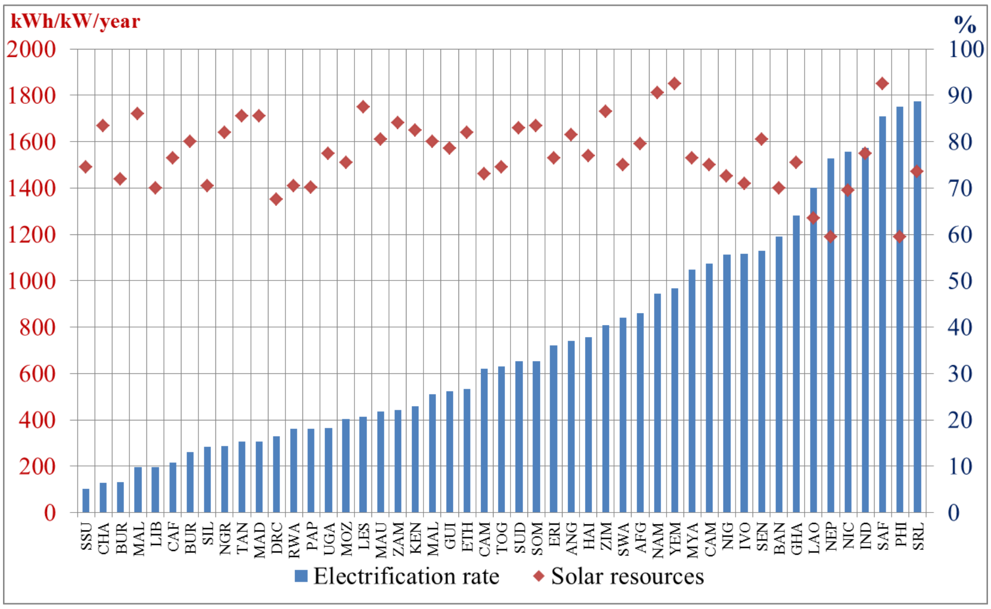


Figure 86: Electrification rate (The World Bank(f)) and PV resources by country (PVgis)[165]

We found that the following countries have the largest population without electricity among the selected countries, but they still have a good solar energy resource potential.

Country	Inhabitants without electricity (million)	Electrification rate (%)	PV power output kWh/kWp/year
India	275	78.7	1550
Nigeria	78	55.6	1450
Ethiopia	71	26.6	1640
Bangladesh	64	59.6	1400
Congo	62	16.4	1350

Table CXIII: Countries with the largest population without electricity

2.1.2 Grid condition & risks

PV development in these regions is not without risk. Even though the risks differ according to each country, the **financial risk** is one of the great obstacles to developing PV markets in these areas. In addition, **institutional risks** can also exist, e.g. a lack of standards or infrastructures. Therefore, it is hardly possible to supply electricity to all residents based on the grid-connection since it is a very expensive solution. Furthermore, many countries among the selected countries have large territories to cover, which lead to high grid extension costs.[166] In this regard, as PV systems have the advantage of being able to provide decentralized power, the utilization of off-grid PV systems seems to be an appropriate solution in these regions. Diesel generators are the classical way of supplying power in these regions (**substitute risks**). Customers also tend to prefer to employ an energy option that generates the lowest initial investment cost (**customer risks**).

2.2 Potential PV market size

In our study, we assumed that PV systems were deployed in the selected countries to increase the power supply for residents with no electricity access via the available energy resources. We describe the opportunities available for the world's energy transition by using solar PV systems in the

[165] The list of selected countries is given in annex
[166] A medium voltage line extension is the cheapest solution for power supply only up to a 15 km distance of the village from the grid. The expansion of a medium-voltage line costs around 45000 $/km and 40000$ for transformers

selected countries. The maximum market size for electrification in the selected countries is defined. The expanded deployment of PV systems in the selected regions would increase their energy independence by improving their energy self-sufficiency. A quick calculation gives the potential market size of PV power in the 49 countries selected.

1) Demand

We have considered that those with no access to electricity would need the same amount of electricity as the average power consumed by the population with electricity. To define a realistic power consumption pattern, we need to determine the average power consumption per capita with electricity access in these countries. We divided the power consumption per capita by the electrification rate based on the country data available from the World Bank. The calculated average is **922 kWh/year per capita** in these countries.

2) Supply

As indicated, the average potential PV power output in these countries is **1548 kWh/kWp/year**. We can conclude that a solar panel of **0.6 kWp/capita** allows us to meet this electricity demand (922 kWh / year per capita /1548 kWh / kWp / year = 0.6 kWp/capita).

3) Potential market size

In conclusion, we defined the total market size for the full electrification in these regions is **about 640 GWp** (0.6 kWp x 1.06 billion people). This results in an electricity consumption of around 980 TWh/year (922 kWh/year x 1.06 billion people).

2.3 Competitiveness of PV power with enlarged global market size

The enlarged PV market size would bring the learning curve effect in terms of PV price decline. We now quantify this effect based on the projected market growth.

2.3.1 Reduced PV system prices

The positive correlation between the module price drop and the size of cumulative installations has been demonstrated in many studies (see Part I). We thus assumed the enlargement of the PV market size would help reduce the price of PV systems (the learning effect). The effect can now be quantified on the basis of the projected market growth (~ 640 GWp). As the PV market grows by embracing such regions, the PV system price can be reduced since it benefits from the larger market size. We considered a learning rate of 18% for the PV system costs in our calculation. The result indicates that PV system prices will be almost halved from the actual of $ 2.13/Wp[167] (IEA PVPS, 2015) to about **$1.3/Wp.**

[167] The cost of the least expensive residential PV system in Germany

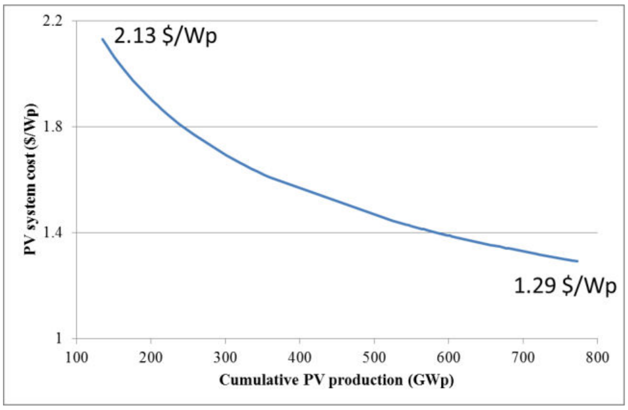


Figure 87: Estimated PV system cost (with a learning rate of 18%)

2.3.2 Reduced PV LCOE

1) Reduced PV LCOE thanks to the enlarged market size

The projected decline in solar PV systems would lead to a reduced PV LCOE. We now calculate PV LCOE in these countries. In our calculation of PV LCOE, we use the cost of the least expensive residential PV system in Germany, 2.13$/Wp in 2015 (IEA PVPS, 2015). Discount rates of 8% and 12% were taken into account because projects in developing countries are more risky than those in developed countries. Table CXIV and Table CXV list the current and future PV LCOEs respectively for certain countries according to their different solar energy resources.

Solar energy resource (kWh/kWp/year)	Current PV LCOE with discount rate of 8%	Current PV LCOE with discount rate of 12%
1800-1850 (South Africa, Yemen, Namibia)	12.5 c$/kWh	15.5 c$/kWh
1500-1550 (India, Myanmar, Uganda)	15 c$/kWh	18.5 c$/kWh
1200 (Nepal, Philippines)	19.5 c$/kWh	24 c$/kWh

Table CXIV: Current PV LCOE in the developing countries (PV system cost: 2.13 $/Wp)

Solar energy resource (kWh/kWp/year)	Reduced PV LCOE with discount rate of 8%	Reduced PV LCOE with discount rate of 12%
1800-1850 (South Africa, Yemen, Namibia)	7.5 c$/kWh	9.5 c$/kWh
1500-1550 (India, Myanmar, Uganda)	9 c$/kWh	11 c$/kWh
1200 (Nepal, Philippines)	12 c$/kWh	14.5 c$/kWh

Table CXV: Reduced PV LCOE with the enlarged market size (PV system cost: 1.3 $/Wp)

1) PV LCOE with batteries thanks to the enlarged market size

We then extended our calculation to PV systems combined with Li-ion batteries for residential applications. We assume the use of 0.6 kWp PV system coupled with a 2kWh[168] batteries because 2kWh batteries can store almost 80% of the average daily consumption.

The LCOE of PV systems coupled with batteries is calculated below:

[168] The daily consumption of ~2.5 kWh/ day is necessary (~2.5 =922 kWh / 365)

$$LCOE\ of\ PV\ system\ with\ battery = \frac{\sum_{t=1}^{n} \frac{I_{PV}^{t} + O\&M_{PV}^{t} + I_{battery}^{t}}{(1+r)^{t}}}{\sum_{t=1}^{n} \frac{E_{PV}^{t}}{(1+r)^{t}}}$$

$$LCOE\ of\ PV\ system\ with\ battery = \frac{\sum_{t=1}^{n} \frac{I_{PV}^{t} + O\&M_{PV}^{t}}{(1+r)^{t}}}{\sum_{t=1}^{n} \frac{E_{PV}^{t}}{(1+r)^{t}}} + \frac{\sum_{t=1}^{n} \frac{I_{battery}^{t}}{(1+r)^{t}}}{\sum_{t=1}^{n} \frac{E_{PV}^{t}}{(1+r)^{t}}}$$

$$= LCOE_{PV} + LCOE_{battery}$$

Solar energy resource (kWh/kWp/year)	Discount rate of 8%		Discount rate of 12%	
	LCOE battery	**PV LCOE with battery**	LCOE battery	**PV LCOE with battery**
1800-1850 (South Africa, Yemen, Namibia)	12 c$/kWh	24.5 c$/kWh	13.5 c$/kWh	29 c$/kWh
1500-1550 (India, Myanmar, Uganda)	14.5 c$/kWh	29.5 c$/kWh	16 c$/kWh	32.5 c$/kWh
1200 (Nepal, Philippines)	18 c$/kWh	37.5 c$/kWh	20 c$/kWh	44 c$/kWh

Table CXVI: Current PV LCOE coupled with 2 kWh batteries (PV system cost: 2.13 $/Wp, battery price: 500$/kWh)

Our calculation is based on the battery price of 500$/kWh (see chapter 1.4). The maximum LCOE of batteries is 20 c$/kWh. The range of the battery LCOE[169] varies from 12 c$/kWh at 1850 kWh/kWp/year with a discount rate of 8% to 20 c$/kWh at 1200 kWh/kWp/year with a discount rate of 12%. Furthermore, battery prices are expected to decrease in the next years based on economies of scale (see Part I). Therefore, the LCOE of batteries will probably fall below 6 c$/kWh in 2030 based on the estimated battery cost of 150 $/kWh.

Solar energy resource (kWh/kWp/year)	Discount rate of 8%		Discount rate of 12%	
	LCOE battery	**PV LCOE with battery**	LCOE battery	**PV LCOE with battery**
1800-1850 (South Africa, Yemen, Namibia)	3 c$/kWh	10.5 c$/kWh	4 c$/kWh	13.5 c$/kWh
1500-1550 (India, Myanmar, Uganda)	4 c$/kWh	13 c$/kWh	5 c$/kWh	16 c$/kWh
1200 (Nepal, Philippines)	4.5 c$/kWh	16.5 c$/kWh	6 c$/kWh	20.5 c$/kWh

Table CXVII: Reduced PV LCOE coupled with 2 kWh batteries (PV system cost: 1.3 $/Wp, estimated battery price: 150$/kWh)

2.3.3 Comparison of PV LCOE vs. LCOE of diesel generators

This section examines to what extent solar PV power is a more **affordable** energy option compared with diesel generators. The diesel power generators (Szabo, et al., 2011) are the competing technologies of off-grid PV systems in these countries. We will compare PV LCOE to LCOE of diesel generators. The LCOE of a diesel generator is 29.7 c$ / kWh to 33.2 c$ / kWh (Lazard 2014 [170]). The fuel price is an important variable when defining the LCOE of diesel generators. We assumed that the

[169] The lifetime of the battery is 10 years: the LCOE of the battery is $\frac{\frac{I_{battery}}{1+r} + \frac{I_{battery}}{(1+r)^{10}}}{\sum_{t=1}^{n} \frac{E_{PV}^{t}}{(1+r)^{t}}}$

[170] With a diesel price at 1.057 $/L

diesel price would stay constant in the future so we could carry out a quick comparison. However, this assumption is limited because it disregards many influencing factors. Based on the previous calculation, we now know that PV LCOE in these regions can vary according to potential solar PV power output and the discount rate. The PV LCOE will increase if we include 2 kWh batteries. Based on our calculation, it can be seen that electrification with the **PV technology is less expensive than the power supply by diesel generators.** In addition, even the combined PV systems with batteries are **more economically feasible without jeopardizing the competitiveness of PV systems when the solar resource is over about 1550 kWh (24 of the 49 countries selected).** Furthermore, if we include negative externalities in the energy system with respect to the generation of large quantities of CO_2 emissions, the real costs of diesel generators will increase.

It is interesting to understand why people use diesel generators for their energy supply. The main differences between the two systems are related to financing; diesel generators require **a low initial investment,** but significant operating costs because of diesel consumption, while PV systems have a large initial investment cost but negligible operating costs. Therefore, we can infer that residents use diesel generators because of their low initial investment costs despite their high fuel costs and negative impact on the environment.

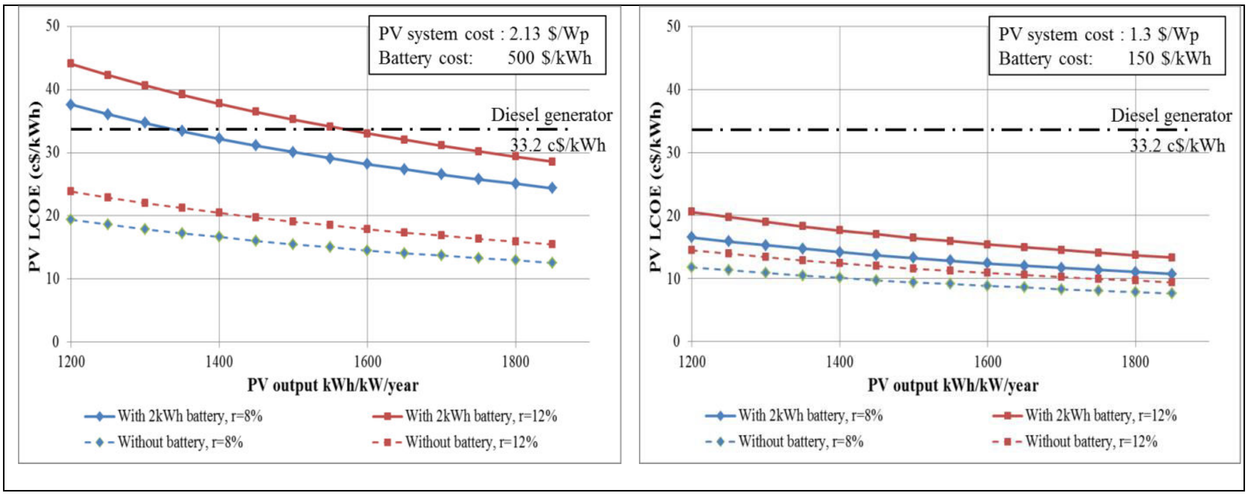


Figure 88: PV LCOE with 0.6 kWp PV system + 2kWh batteries based on discount rates of 8% and 12%: current PV LCOE (left) and reduced PV LCOE (right)

2.3.4 PV domino diffusion strategy model

How can we roll out PV diffusion in the selected countries at the lowest possible cost? We will now attempt to propose a smart strategy which maximizes the reduction of PV policy costs based on the projected enlarged market size. We assumed that PV systems were installed in consecutive order from the country with the highest solar energy resources to the country with the lowest solar energy resources (see annex). This PV diffusion strategy allows these regions to take advantage of the gradational decline in PV system costs based on feedback from the market development (the larger the market scale, the lower the PV system cost). The last installer will benefit from the lowest PV system costs. We have named this the ‘PV domino diffusion strategy model’.

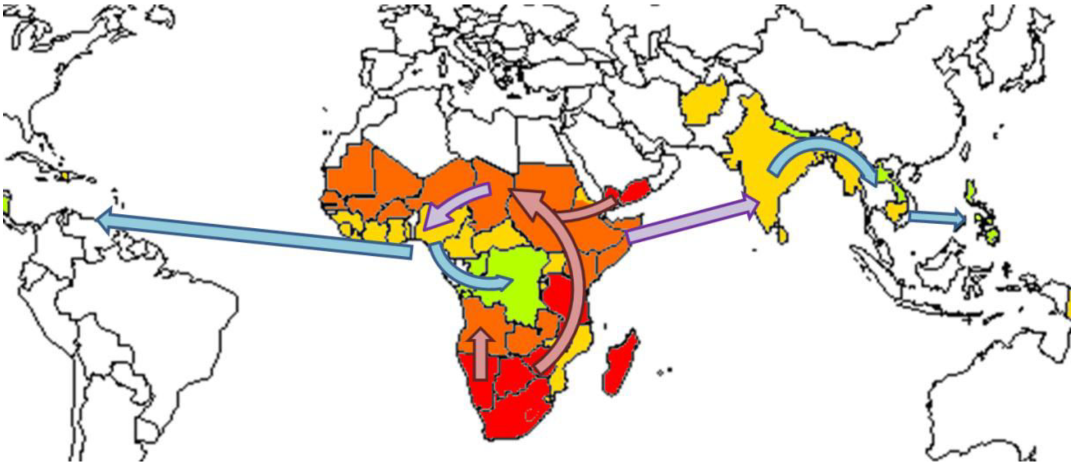


Figure 89: Optimal PV diffusion – 'PV domino diffusion strategy model' for electrification of regions with no access to electricity (author's proposal)

The current PV LCOE is shown in **Figure 90** (in blue). The red bar graphs represent the reduced PV LCOE in all 49 countries thanks to the gradational diffusion strategy of PV installations. As the PV market grows, the PV LOCE will be reduced based on the learning effect. We can see this strategy results in a similar **PV LCOE of around 13 c$/kWh across the defined countries.**

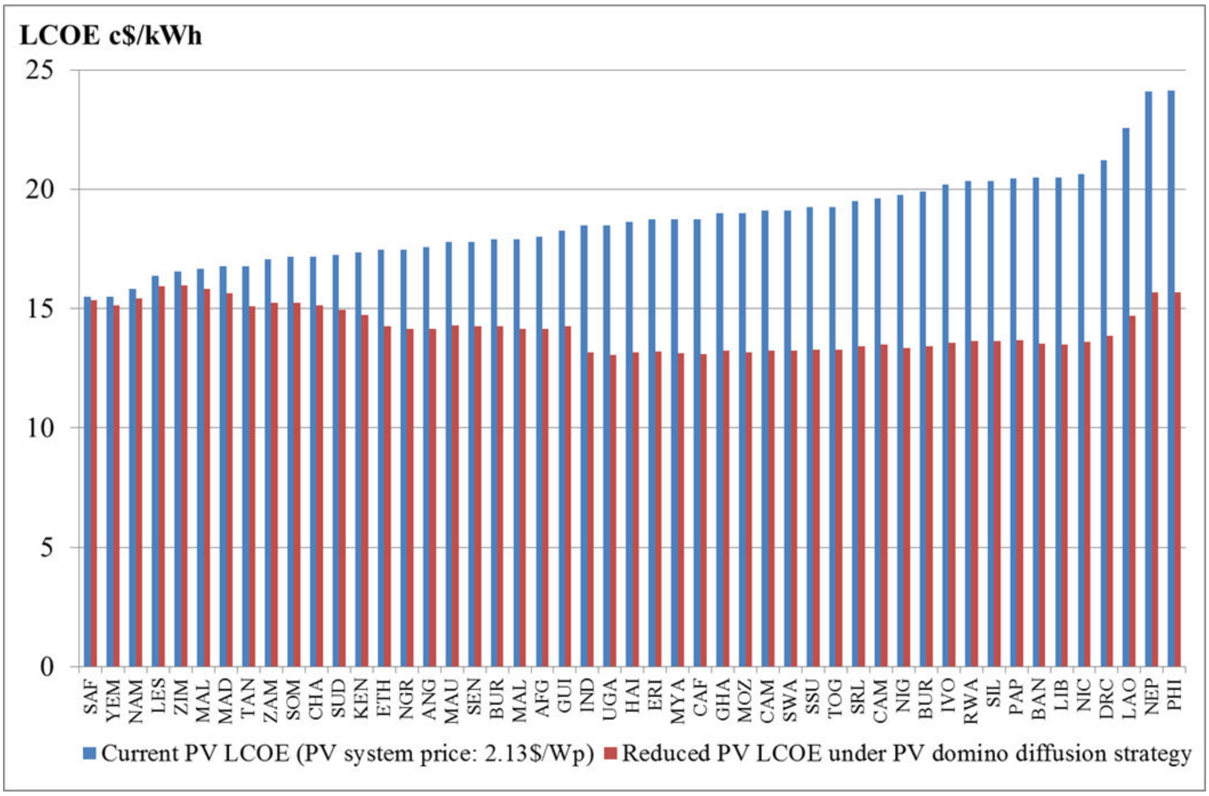


Figure 90: Reduced PV LCOE with the PV domino diffusion strategy model (in red) vs. current PV LCOE with a PV system price of 2.13$/Wp (in blue) (author's proposal with 12% discount rate)

2.4 Costs and benefits

2.4.1 Costs

We assumed that international policies were now aiming to install PV systems to supply power to 1.06 billion people without any access to electricity. The total requirements for electrification in the 49 countries according to two different scenarios can now be calculated. Without any strategic diffusion efforts, the total costs of full electrification in these regions represent around US$ 1,363 billion based on the current PV system price (640 GWp x $2.13 /Wp, the total energy consumption demand x PV system price). Yet if we apply the proposed PV domino diffusion strategy model (PV installations in the order of solar energy resource from the highest to the lowest), the required costs can drop to **US$ 980 billion.**[171]The proposed PV domino diffusion strategy model helps to reduce policy costs.

	Electrification costs with current PV system costs (2.13$/Wp)	Electrification costs with PV domino diffusion strategy
Total policy costs of the support	US$ 1,363 billion	US$ 980 billion

Table CXVIII: Electrification costs for all inhabitants without electricity

2.4.2 *Benefits*

We summarize the expected benefits from the targeted deployment of PV systems using key variables of the proposed schematic map.

Energy transition	Possible PV installations: 1.03 billion x 0.6 kWp = **640 GWp** Electricity production: **around 980 TWh/year** (922 kWh/year x 1.06 billion people)
Economic benefits	**New outlets for oversupplied PV industry** Sustainable socio-economic development in the developing countries based on green growth model
Land usage	640 GWp x 7 GWp/m^2 = **4,480 million m^2 available without new land use** (with 7m^2/kWp, cf. Part I chapter 2)
Grid-level costs	Off-grid usage thus **no impacts**
Environmental benefits	**1499 MtCO$_2$/year** (1528 MtCO$_2$/year-49 MtCO$_2$/year) can be **avoided** compared to the use of diesel generators.
Competitiveness of PV system	The reduced PV system prices from around $ 2.13/Wp (IEA PVPS, 2015) **to $1.3/Wp** Reduced PV LCOE

Table CXIX: Expected benefits of the PV market development in developing countries

1) Economic benefits (solutions for the oversupply & new market growth)

As presented, the global PV industry reacted to the oversupply situation with even fiercer international competition. The PV industry crisis increased difficulties for countries aspiring to implement green growth policies with the combined policy objectives of energy transition and economic growth through PV growth. In addition, long-lasting trade disputes between countries (e.g. China vs. US, and China vs. EU) narrowed the scope of the PV market for the relevant countries. However, the national PV policy framework is limited to solve these issues; the increase in the domestic demand may in fact be insufficient to support the globalized PV industry with GW-scale production capacity.

In this regard, the proposed opportunities to include new frontiers for the global PV market growth would provide the PV industry with new outlets for the current oversupply of PV products. This approach expands the scope of the global PV market within the international context so as to solve the current PV industry's anxiety. Furthermore, new regions could also benefit from the sustainable energy supply system for their socio-economic development. In particular, this solution

[171] The full coverage of PV installations in 49 countries reduces the PV system price, and this reduced PV system price was used to calculate the cost of PV installations in the next country. The calculation was performed until all the countries were equipped with PV systems: $\mathrm{Cost} = \sum_{\mathrm{countries}\ c}(\mathrm{Price}^c \times \mathrm{Market\ size}^c)$

provides an interesting option to address the problem of world energy poverty. It would increase the world's electrification rate and eventually have a positive impact on the global economic growth.

2) Environmental benefits (reduced CO2 emissions)

We aim to examine to what extent solar PV power is a more **environmentally friendly** energy option compared with diesel generators. As defined, a total of 980 TWh/year is needed for the full electrification in the 49 selected countries with the average consumption of 922 kWh/per capita/year. The CO_2 emissions will differ according to the energy technology employed. If we supply electricity with diesel generators, it will produce more than 1500 Mt CO_2 per year. This amount accounts for almost 5% of the current global emissions, i.e. 32.2 Gt CO_2/ year (IEA, 2015b). Therefore, we can conclude that PV systems provide a solution for electrification in a more eco-friendly way. **About 1500 MtCO_2/year** (1548 MtCO_2/year-49 MtCO_2/year) can be **avoided** compared with the use of diesel generators.

Technology	Life Cycle Assessment gCO_2/kWh	Total emission MtCO_2/year
PV [172]	50	49
Diesel generator[173] (small < 60 kW)	1580	1548

Table CXX: CO_2 emissions per kWh for PV and diesel generators

2.5 International financing

Our proposed solar PV electrification program for 1.06 billion people with no access to electricity falls in line with international objectives to combat climate change and to provide a global sustainable development model. In addition to improving the world's energy sustainability with environmental, social, and economic benefits, it also provides strategic orientations for PV growth by broadening its market frontiers on a global level. As the nation-wide PV policy system became more complex with the globalization of the PV market, breakthroughs in the current PV market should be considered in line with the global dynamics and as part of an internationally collaborative approach.

However, the main barriers are financial risks as PV installations require high initial investments. Considering the fact that the defined opportunities address several global problems like energy poverty and climate change, it seems fair to consider international funding to implement the program as part of actions to increase the global energy sustainability. Funding should come from a wide variety of governments, civil society and private sectors to support the switch from fossil fuels to greener sources of energy in pursuit of global environmental and economic benefits.

At the Paris climate change conference (COP21) in December 2015, it was decided that the developed countries are involved in jointly making the international climate finance to support developing countries: **international climate finance** of US$ 100 billion a year in climate finance for developing countries by 2020, with a commitment to further finance in the future (COP21/CMP11, 2015).

[172] (NREL, 2012b)
[173] (Moss & Gleave, 2014)

The funding will come from a wide variety of public and private, bilateral and multilateral, and alternative sources of finance to support the switch from fossil fuels to greener sources of energy and the adaptation effects of climate change.

Therefore, our proposed solar PV electrification program in new regions fits with the COP 21 objectives to address climate change issues and provide a sustainable development model in these regions. The program has several favorable conditions to receive such climate finance.

- Land usages: It is important to note that the agreements of COP 21 to address climate change and reduced CO_2 emissions in a manner that does not threaten food production (article 2 (UNFCCC, 2015)). This gives a favorable condition to PV projects because PV installations can use the existing surfaces.
- Reduction of CO_2 emissions: We conclude that the electrification with PV systems produces produce fewer CO_2 emissions compared with diesel generators (the classical way of supplying power in these regions).
- Global economic benefits: The defined new market can be outlets for PV oversupply. In addition, this can provide a sustainable economic growth model in these regions.
- Good solar energy resources: The investment costs will be inferior to other regions, because the studied countries have better solar energy resources.

The COP 21 decision on the international climate finance will give a political signal for the private sector investment choice. Major PV material producing countries can invest to support PV installations in these regions to create new demand. Furthermore, finance models can adapt the revenue patterns in the regions by taking income characteristics which are small and irregular into account (e.g. microfinance).

2.6 Global virtuous circle in the PV sector

We have demonstrated that the proposed opportunities address climate change issues and provide a sustainable growth model in these regions. However, the selected regions are most likely to be reluctant to invest in PV installations due to their difficult financial situations. This explains why these countries may prefer to continue supplying diesel-based power to residents despite the high costs. In this regard, international efforts will be necessary if we intend to roll out this electrification program. Such actions should involve not only governmental levels, but also the private sector and civil contributions. It is expected that this program will eventually benefit the global economy and the future energy systems of participating countries. New market development is necessary to generate new outlets for the global overproduction of PV products. By broadening the scope of the potential PV market to cover the entire international arena within an open economy, the investment to increase the foreign demand of PV installations will be partially returned to the domestic industry growth of participating countries. It will drive the growth of the global PV industry since the existing PV market growth is limited compared with the supply capacity. In addition, PV costs would be reduced thanks to the enlarged market size and experience. It is important to note that the enhanced competitiveness of PV power would eventually contribute to future national-based installations in all relevant countries with reduced PV costs. Based on our model, the energy transition can be implemented within an international context. Therefore, all stakeholders would benefit from this approach that encompasses new regions with improved energy access regardless of the political objective (industry or energy transition). As a result, a 'virtuous circle' in the PV sector can be produced on an international scale.

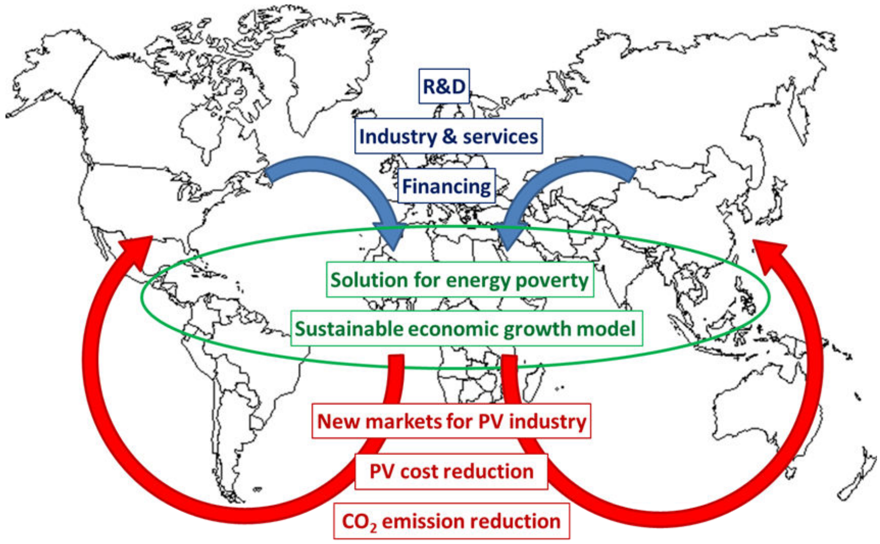


Figure 91: Global 'virtuous circle' in the PV sector (author's proposal)

3 Improvement of PV system competitiveness in non-module sector

We now propose another opportunity for cross-country cooperation. The aim is to enhance the competitiveness of PV systems by improving non-module sector (we are now aware of room for improvements in this sector). This allows advancing time of PV self-consumption in the residential sector. The international cooperation gives opportunities to transfer the advanced standards. In this regard, we attempt to show how the share of common standards among countries can increase the PV competitiveness with a focus on non-module sectors. In addition, we quantify the effect assuming a common market between three European countries. If we include broader geographic regions, the effect would be greater. At the end, we conclude with some suggestions of policy actions.

3.1 Introduction

The further reduction in the production costs of PV electricity encourages the widespread use of PV power as a major electricity source. We demonstrated the key components of PV system prices in order to penetrate the current energy systems. Module prices are not as important as before and other non-module factors have gained equal importance when it comes to improving economic competitiveness. In this regard, policy focus also integrates these factors to gain further competitiveness. Our study attempts to review opportunities with harmonized policy instruments on a regional level so as to reduce non-module costs of PV systems. We quantify the opportunities restricting in Europe by learning from German practices and benefiting from the size of the European market. However, this approach can be applicable to other regions.

3.2 Opportunities of reducing non-module costs for the European market

We have demonstrated the size of the market is related to the non-module price drop (see Part I). Our study aims to explain some opportunities for the European market on the condition that they share unified standards based on the German practice with a simple calculation process. If the west European region uses the same learning curve as Germany (17.6%, see Part I chapter 2), it would require less investment to deploy PV systems. **Figure 92** shows the non-module price in 2020 on the condition that the German learning curve is shared along with properly designed policies.

The case is simplified by taking into account the residential installation conditions in three countries while country system differences are ignored. The installation total for 2020 has been calculated based on the sum of three countries, assuming the same annual growth rate up to today[174] until 2020 for France and Italy, and EPIA estimations were taken for Germany with the same residential PV system share (EPIA, 2014). They will roughly reach **0.98$/Wp for the non-module price**. However, better results are obtained in terms of the prospective non-module prices if more countries are included since a larger market size is taken into consideration.

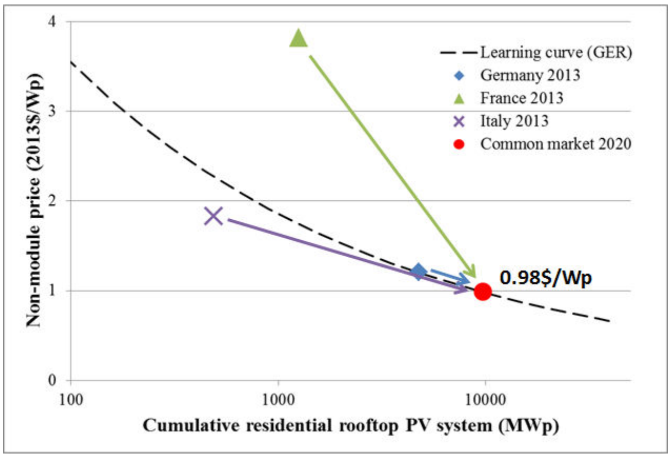


Figure 92: Common learning curve for Germany, France and Italy under German standards

Therefore, the long-term durable market growth is important. The European market could learn from this experience to develop its PV systems to meet its objective to increase renewable energies in the energy mix. By adopting the German practice, countries like France will be able to install the higher number of PV systems on the same budget thanks to the lower non-module price.

Figure 93 explains the benefits of reduced non-module costs with France case. The reduced non-module cost allows the country to reduce policy costs to support PV installations or to obtain targeted LCOE earlier.

[174] Assumption is the cumulative installation of PV rooftop systems in France, Germany and Italy. The total cumulative installation will be about 11600 MWp based on prospective growth.

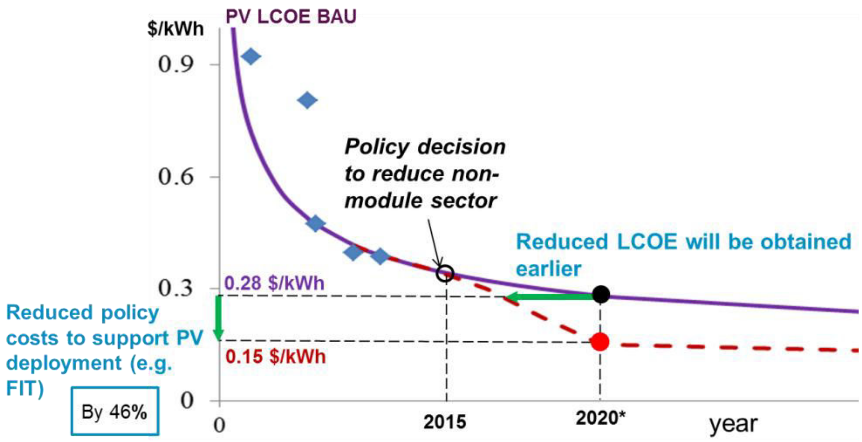


Figure 93: Benefits of reduced non-module costs: France[175]

This begs the question as to what conditions can generate such opportunities. Each country currently has a different policy focus, with different installation environments and market development stages; these factors lead to different costs for PV installation. To reduce non-module costs in PV systems, countries can share markets and policies with a clear growth trajectory plan. Targeted policy support helps this process. Harmonized policy instruments on a regional level can reduce non-module costs in Europe by learning from the German practice (e.g. low non-module prices) and taking advantage of the size of the European market.

3.3 Policy recommendations

Which policy instruments can help obtain the estimated benefits? Targeted policies can further reduce non-module costs to improve the economic competitiveness of PV electricity. The increased market size is an important factor to reduce such costs.

Economies of scale in installations can be obtained by promoting the **standardization of PV installation.** Standardization improves the economic competitiveness of almost all segments in non-modules; hardware price, engineering, PII process, customer acquisition and installations. Once standardized products and processes are rolled out, the market will automatically adapt without spending costs to continue tasks in these sectors (e.g. system design, adapting different installation specifications, etc.). In addition, a **simplified process** from project design to grid connection is needed. Transparent online permission processes with clear guidelines is one way of simplifying the whole process. The online tool can be also used line up customers with certified local installers. The European system for **certifying** PV firms based on European standards could be implemented. Furthermore**, training** is also important; well-trained installers and customers will remove additional time in terms of system design and installation work.

In addition, the **long-term stability** of the market size can be driven by regional solar mandates in the building sector (new, renovation of existing buildings) or favorable policy support that gives investors a clear long-term vision like installation subsidies, well-designed financial support or

[175] PV LCOE of 0.15$/kWh: author's calculation based on estimated PV system cost of 1.7 $/Wp (in 2020: 0.96 $/Wp + 0.7-0.8$/Wp) (IEA, 2014). French estimated residential installation in 2020: 3.7 GWp.

tax relief. A standardized European market is one way of gaining economic competitiveness to provide PV electricity at a low price. Therefore, a commonly shared practice for PV deployment could help improve European economic competiveness and thus largely reduce the PV system price.

However, this does not directly mean cheap electricity will be obtained using PV energy. As explained, with broad penetration of PV system, other costs or externalities issues can be more visibly important for the future system. Reduced production costs can be counterbalanced by factors such as grid costs (e.g. grid extension, intermittency costs) unless proper policies are applied to improve alignment with non-module sector improvement. The cooperative strategy should also consider the systemic view.

4 Conclusions

We have proposed opportunities of further PV growth based on cooperative actions among countries. First, we proposed an expansion of electrification in less-developed and developing countries. The defined markets cover major energy poverty regions with good solar resources, representing 1.06 billion people without electricity. PV off-grid systems give an interesting option to solve the energy problem in these countries by addressing institutional risks (lack of infrastructures). They can replace diesel generators (substitute) and generate less CO_2 emissions. We defined the total market size for the full electrification in these regions is **about 640 GWp.** In addition positive feedback can exist from the market development with respect to the PV system price (learning curve effect). In this case, PV system prices will be almost halved to about **$1.3/Wp.** By benefiting from gradational decline in PV system costs in 49 countries (PV domino diffusion strategy model), PV LCOE in these countries will be around 13 c$/kWh. This requires a total of US$ 980 billion investment to realize this program. PV cost reductions and international policy approaches will help solar energy make inroads into new markets, particularly where the access to electricity is very low. The enhanced PV competitiveness benefiting from enlarged market size and experience will give positive feedbacks on the future nation-wide installations in developed countries. In addition, the investment would give engine for growth in global PV industry.

Secondly, we proposed another idea of cross-country cooperative actions. It aimed to reduce PV system costs with a focus on non-module sector (the current cost driver). Countries can consider commonly designed policies in order to create a common market based on standardization; this will help reduce non-module costs, in particular for the residential system. The enhanced economics of PV system will allow more people to access to the PV electricity in the future. This would advance time of PV self-consumption in residential sector.

Conclusions of Part III

PV power has largely gained economic competitiveness over the last decade. It reaches a turning point when it attains grid parity. However, it is also possible for consumers to consider installing their own PV systems to reduce their energy bill since their decision is based on electricity tariffs that they pay. The increased competitiveness of PV systems would increase the individual energy independency. However, it also raises new issues in terms of the national energy mix since policymakers need to consider an optimal mix of PV power that balances with other energy technologies and grid financing. However, the increased competitiveness of PV definitely gives opportunities to further develop the use of PV power in the current and future energy mix.

In this regard, we suggested smart strategies of using PV systems. The aim was to provide the necessary elements that help policymakers prepare more effective PV public policies in the future. In order to deploy the self-consumption model at the lowest cost, our study has shown the interest of prioritizing sectors that guarantee 100% onsite consumption like supermarkets. We quantified opportunities of PV installations by assuming all surfaces of the existing supermarkets in France are used for PV self-consumption. Our study has demonstrated that 100% PV self-consumption based on the distributed PV systems would provoke less systemic costs than other types of PV systems (e.g. utility-scale PV plants). The suggested supermarket model can allow France to reduce the systemic costs by up to 30% at 10% PV penetration. In addition, compared to FIT system (the current demand-side policies), we concluded that 100% PV self-consumption is less costly in the electricity system with less direct policy costs. It can also help avoid windfall effects that appeared under FIT system.

In the future, this approach can be extended to other sectors with poorer matching profile (e.g. residential) when PV systems are combined with batteries. We concluded that residential systems coupled with batteries are now profitable in Germany and can be profitable before 2030 in France based on the IEA's scenarios. If PV systems were deployed on all French individual houses for the purpose of PV self-consumption, this would give around 56 GW of PV systems installed in France (~12% of French electricity consumption). However, our study did not ignore losses of stakeholders caused by PV integration with self-consumption model. In particular, losses related to the grid management are critical with regard to the security of the national electricity system. In the current electricity system, the grid management costs are integrated in electricity tariffs. However, fewer consumers would participate in paying this even though PV systems should be connected to the grid to secure the stable supply of electricity (our study quantified the losses). In the future, more people will naturally consider shifting to this mode of PV power use as PV systems enhance its economic competitiveness. The government should prepare for this important transition before the national electricity system encounters social pressures that cause significant changes.

The proposed strategic orientations for PV growth extended its market scope to include the international arena as the PV sector is now globalized. We proposed opportunities of further PV growth based on international cooperation. The aim was to find new market equilibriums to solve the current turmoil of PV market with oversupply and long-lasting trade disputes. We presented specific opportunities with quantified data. Our study concerned the expansion of electrification for 1.06 billion people in less-developed and developing countries. Our calculation gave the potential market size of 640 GW. In order to realize these opportunities, we need around a total of US$ 1 trillion investment. We highlighted benefits from the market development in these regions as below:

- New outlet for overproduction of PV products
- Solution to address the world energy poverty problem
- Develop a sustainable energy system in the regions: almost 1500 Mt CO_2 can be avoided compared to the substitute (e.g. diesel generators)
- A decline in the PV system price to $ 1.3/Wp benefiting from enlarged size of PV market and experience (learning curve effect).

We also highlighted positive feedbacks of market development on the global PV installations. The enhanced competitiveness of PV power will eventually contribute to future nation-wide installations of all relevant countries based on reduced PV costs. The energy transition can be implemented in the international context.

We have also proposed other opportunities for cross-county cooperation to gain more competitiveness of PV systems. We provided recommendations on how to further reduce PV system costs by focusing on non-module sector. The targeted policy with standardization in European region based on the German best practice can reduce the non-module price below 1 € / Wp. If this idea brings good results, more countries can adapt this approach to make the larger common market. This approach would also help advance time towards PV self-consumption. The international cooperation can be further developed related to other sectors like green buildings, green infrastructures, and systemic impacts.

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Conclusions

1 Summary

The study included the parallel analysis over several time periods to highlight the dynamics of the national policy mechanisms. The principle of 'virtuous circle' of Watanabe (Watanabe, et al., 2000) was applicable at national level until the mid-2000s, as long as the policy is sufficiently ambitious and stable with the long-term vision. However, we demonstrated **this nationwide dynamics was broken with the arrival of China in the PV sector** based on our cross-country analysis. The study allowed us to define the interactions among different policy strategies and consequences in the global PV sector.

Under the globalized PV market, the PV system prices have been largely reduced over the last decade in many countries. With the sharp decline in PV system prices, the PV self-consumption becomes attractive in some areas. The thesis demonstrated that this model is more economical solution than financing by the FIT scheme and helps minimize the systemic effect in contrast with on-grid utility-scale PV systems. Furthermore, this mode of PV power use would bring organizational changes and new business models. Therefore, it is also mandatory to think about the secondary impacts on stakeholders, in particular on the network management. The transition to this usage reduces the electricity consumption from the grid; it is thus possible to identify losses of traditional stakeholders based on electricity tariffs to prepare mitigation policy actions towards any policy risks created from the most influencing group of stakeholders (grid operators, conventional energy producers, and consumers).

Concerning the development of PV self-consumption model with the use of decentralized PV systems, the thesis focused on opportunities offered by the existing French supermarket surfaces in the short-term. The development of this niche sector has much value because it gives policymakers a large-scale experience of PV self-consumption to anticipate risks and impacts on the whole electricity system. In the longer-term, the study has shown that PV self-consumption with battery could become profitable in France before 2030. The demand in the residential sector would thus be natural in the next 15 years in France; it represents a significant share of national power consumption. If policymakers aim to promote this model, our thesis also proposed ways to reach the breakeven point sooner by improving the PV economic competitiveness in non-module sector. We demonstrated the collaborative policy actions on a regional level can reduce non-module prices of residential PV systems in Europe by benefiting from the experience of the German practice (e.g. low non-module prices) and the size of the European market.

Policymakers will have to embrace the change. In order to prepare the natural demand in PV self-consumption, we recommend that it is very important to have a regular and progressive policy in terms of the transition to PV self-consumption in the future. It should aim to 1) give enough time for traditional electricity producers to adapt to the new market situation, 2) provide PV firms and investors with a stable and long-term policy signals and 3) reduce the negative impacts on the electricity mix by adapting to the age of production capacity in use.

In this regard, this thesis expects the gradual **shift in PV policy** f**rom a policy in favor of PV growth to a regulatory policy to limit systemic impacts of PV integration** in the electricity system. It should aim to avoid rapid and chaotic diffusions of PV self-consumption model in the future. The future PV policy should be decided based on systemic perspective taken the costs for the whole energy sector into account.

Finally, the thesis proposed a pathway to escape from the current PV industry crisis. Our thesis has shown difficulties and challenges of PV policy implementation interacting with the complexity and dynamics of policy system. Based on our analysis, we understand the importance of a regular increase in demand with stable and long-term policy signals in order to seek employment stability in the PV installation sector. However, this national strategy would reach the limit; the increase in the domestic demand may be insufficient to support the globalized PV industry with GW-scale production capacity and induce additional costs related to systemic impacts without strategic orientations. The national policy for PV installation growth should be prepared in the context of electricity mix evolution with long-term strategic perspective. In this regard, in order to solve the global PV industry crisis, we can consider extending the scope of the political strategy to stimulate the demand to the international context.

In this regards, in return for a stop of Chinese subsidies to the PV industry, it was proposed to define international policies of global collaborative actions to provide new outlets for PV overproductions. The expansion of electrification, using off-grid PV systems, in developing countries with no access to electricity was studied. This problem concerns around 1.3 billion people and this policy would provide a sustainable socio-economic development model in the world's poor regions. Therefore, the proposed opportunities can solve several global sources of anxiety. It contributes to reduce the global emissions of CO_2 compared to a business as usual (BAU) scenario, to give an engine for growth to the global PV industry, and finally to bring a sustainable development model in the developing countries by increasing access to electricity. The proposed PV domino diffusion strategy model enhances benefits by further reducing the PV system prices and policy costs. The enhanced competitiveness of PV power benefiting from the enlarged market size and experiences would eventually contribute to future national installations with reduced PV costs. All stakeholders would derive benefits from this approach, regardless of their political objective (industry or energy transition). As a result, we reproduce **a 'virtuous circle' in the PV sector, but this time on a global scale.**

2 Contributions

Our systemic approach provided a concrete overview of PV policy mechanisms including all relevant variables, dynamic features and stakeholders. The systemic approach and methodologies that were proposed in this thesis would be beneficial for all stakeholders involved in the PV policy mechanisms. The main contributions are presented as below.

A systemic vision on PV policy mechanisms

This thesis provided **a systemic perspective of the evolution of the PV sector** embracing the relevant areas in supply and demand side, policy context and dynamical change. The systemic analysis that was conducted in this thesis included a wide variety of research topics to understand each segment of a system and to highlight links between sectors. It also intended to keep an objective point of view to the PV sector to analyze the impacts of PV integration in energy system. Therefore, compared to existing studies on the subject, this thesis gave a **complete systemic vision** of PV sector including the **dynamic features** of the system. In addition, several countries' data of both supply (R&D, industry) and demand (installations and systemic impacts) side were compiled over several years in a consistent way using a common methodology. The approach can be reused for the analysis of future evolution of PV sector.

Methodological contributions for a systemic analysis

The thesis proposed **structured mapping methodologies according to a systemic approach to understand the complex mechanisms** related to the PV development. The first mapping gives a general **macroscopic vision to policymakers with a clear summary of PV policy system** linking from political context and objectives to results and impacts. This can be used for policy reporting and evaluation process.

The proposed three detailed mappings provided useful tools to define the causal relations between key variables that influence the core variables (PV power growth, economic benefits through PV industry development and the real costs of PV power in the electricity system). Since all variables can be quantified, this tool can be used to measure policy efficiency. These mappings give a concise but precise insight to 1) **understand the PV sector mechanisms on how public policies influence the defined core variables** 2) **identify the problematic points** between key variables that can be influenced by policy actions and the core variable, and 3) eventually **measure policy efficiency.** This methodology can be interesting for policymakers to make policy decision in the PV sector or for the future studies on policy assessment.

An insight into a change in PV policy dynamics

Our thesis implies the possibilities of change in the nature of PV public policies in the future. Until now, the main objectives of PV public policies concentrate on stimulating PV demand to help reduce PV costs. However, as the socket parity for solar PV power is reached in many countries, the increased demand in PV self-consumption in the future would change the nature of PV public policies. The preparation for this transition would be one of the most important roles of PV public policies. They would have **regulatory roles** with the objective to limit systemic impacts of PV integrations in the electricity system.

This thesis also provided another insight into **a change in PV policy mechanisms from nationwide to global dynamics**. From the supply-side perspective, even though the PV sector has shown the constant growth over the last few decades, the global PV industry encountered the industry crisis with a very tough international competition. This PV industry crisis gave more difficulties to those countries that aspire to implement green growth policies with the combined policy objectives of energy transition and economic growth through the PV growth. We highlighted the complexity of the national PV policy mechanisms was enhanced with globalization. This finally created more policy challenges to the relevant countries. In this regard, we also proposed to extend the scope of strategy to solve this industry problem to the international context.

3 Limits of the thesis

The work presented in this thesis has several limitations related to limited access to data, vast issues of electricity market, analysis tools or simply due to time constraints.

Access to data

First, the thesis focused on crystalline silicon technology. Given the fact that this technology represents around 90% of the market, this choice is understandable. In addition, this PV system prices have been largely reduced in recent years and there are still room for further reduction. A lock-in effect by this technology probably exists. To define this problem, a more precise study on economic prospects of other technologies could have been done. However, this work was difficult to conduct due to the lack of technological expertise and data on detailed costs.

Furthermore, barriers to accessing data gave limits to our analysis. Unfortunately, the measurement of policy efficiency has been insufficiently done due to the lack of data (e.g. industry policy support, production costs). In addition, even though the reduction of CO_2 emissions is one of the important advantages of renewable energy use, the assessment of PV impacts on CO_2 emission reduction is rarely conducted. Data on CO_2 emissions are available, but the analysis of PV's contribution should be done prudently based on systemic perspective. For example, when Germany and Japan increased PV power in their electricity mix, they have also experienced significant changes related to policy context (e.g. decline in the share of nuclear power, economic downturn). Under this context change, it was no longer possible to clarify to what extent CO_2 emissions were reduced by PV penetrations. We thus decided not to include those data in our study. Furthermore, we could have done better demonstrated the complex interactions between Germany and China if we had precise data on Chinese policy input in PV industry and economic damages for each player.

PV integration in electricity market

This is an important point related to the development of PV power. While we defined a problem concerning this issue, the thesis did not propose solutions to address negative externalities that exist in the electricity market. We considered that it is out of the scope of this thesis since our study focused on PV policies. This issue can be another thesis subject itself. However, it is important to follow the evolution of the electricity market because it gives a significant impact on the PV sector.

Similarly, the thesis gave a limited perspective in terms of storage solution of electricity. We decided to take Li-ion battery technology to study the opportunities of PV self-consumption in residential sector. Many other promising technologies exist, but the analysis based on the well-documented Li-ion technology gives a basic scenario.

The seasonal storage solution has not been discussed in the thesis. Even though it is not expected to be available in the short to medium term, it can largely solve the problem related to the intermittency of PV. The study on the seasonal storage solution should be conducted associated with the whole electricity market because it concerns diverse aspects like the network management, the intermittent low-carbon energy sources, and dispatchable technologies with low flexibility.

Analysis Tools

Finally, the thesis used the learning curve theory. It is a tool that has proven itself and is widely used in the scientific research to predict changes in technology costs. However, we can still raise a question on the utilization of learning curve because it remains essentially an empirical tool. In this regard, in our study, the utilization of the learning curve is limited mostly for 15 year time period in order to reduce the level of uncertainty.

4 Future researches

This study intended to keep a global vision that leads to the construction of systemic tools of PV policy mechanisms. We also tried to conclude the thesis without prejudice to specific policy objectives. Once the systemic vision on the PV policy mechanisms is built, it would be interesting to apply the methodology and recommendations proposed in the thesis to specific cases. **An in-depth country study** is possible using the proposed methodologies. In order to provide concrete analysis, it is necessary to find numeric values of each variable. Once the maximum level of data is collected, it would be possible to measure the efficiency of current policies.

To give the most comprehensive analysis, it is very important to accomplish an **advanced study on externalities** to quantify them. In particular, it would be interesting to take the age structure of existing power capacities into account. In addition, all anticipated closing costs of power production capacity as a result of the increased penetration of PV in the electricity mix should be considered. The study also concerns job balance including externalities such as job shifts from conventional power sector to PV industry. The use of backup and balancing sources should not be ignored when calculating CO_2 emission balance.

The study also proposed possibilities of international collaborative actions to increase electricity access in developing countries to exit the global PV industry crisis. This would bring a set of benefits to stakeholders involved with positive feedbacks in the PV sector. In accordance with the Paris Agreement, the future study can further investigate **mechanisms of financial solutions** to realize this idea.

In addition, as PV systems have the advantage of being able to provide decentralized power, this technology is thus often cited for the coupling with other sectors. Therefore, it is possible to **extend the use of the proposed tools and our study in liaison with other sectors like transportation and energy.** The advantage of this solution is to enlarge the PV power's potential market towards the whole energy market. In addition, it allows policymakers to have a broader base to reduce CO_2 emissions.

Another interesting area of research concerns the **study on the development of technological breakthroughs in associated with the industry policy**. When a country aspires to develop PV industry with technology breakthroughs, the research should include both the supply and demand side. From the supply-perspective, the country's competency should be evaluated with an analysis to identify the level of each PV technology skill and define the distance to the technology frontier. The strengths and weaknesses of each technology compared to crystalline PV should be also examined since the market is heavily dominated by this technology. The future total costs for each technology can be estimated by decomposing the actual costs of laboratory technologies and referring to experience of crystalline PV technology. In terms of the demand-side perspective, the market can be defined associated with new usages that can be designed by available technology. High value-added markets can be thought for the new business creations like global green building market. The mappings can help prepare strategies for the international competition and define the size of local and global market. It is also important to think over how to stimulate the private investment to realize the defined business opportunities.

Publications and conferences

Publications in scientific journals

'**Solar Photovoltaic Energy Policy and Globalization: a Multi-perspective Approach with Case Studies of Germany, Japan, and China**', *Progress in Photovoltaics: Research and Applications*, April 2016, Volume 24, Issue 4, p. 409-587 (Hyun Jin Julie Yu, Nathalie Popiolek, and Patrice Geoffron), http://authorservices.wiley.com/bauthor/onlineLibraryTPS.asp?DOI=10.1002/pip.2560&ArticleID=1405823 (published online 17 November 2014)

'**Historical Evolution of South Korea's Solar PV Policies since the 1970s**', *Annales Historiques de l'électricité,* Public Policies of Solar Energy, 2013, Volume 11, p. 87-104 (Hyun Jin Julie Yu, Nathalie Popiolek)

'PV Development Opportunities in the International Context', *Energy Policy* (to submit)

'PV Self-consumption and Role of PV Policies', *Energy Policy* (to submit)

International conferences with proceedings articles

'Solar Photovoltaic Development Opportunities in New Regions with a Global Virtuous Circle', *23rd World Energy Congress (WEC2016),* 10-13 October 2016, Istanbul, Turkey (accepted)

'**Economic Attractiveness of PV Self-consumption in French Residential Sector and Impacts on Stakeholders**', *34th USAEE/IAEE North American Conference*, 23-26 October 2016, Tulsa, Oklahoma, USA (submitted)

'**Challenges and Opportunities of Photovoltaic (PV) Growth with Self-consumption Model**', *38th International Association for Energy Economics (IAEE) International Conference*, 25-27 May 2015, Antalya, Turkey (Hyun Jin Julie Yu, Nathalie Popiolek)

'**A Comprehensive Approach to Evaluate PV System Prices and Opportunity for PV Policy**', *12th International Conference on the European Energy Market (EEM 15),* 20-22 May 2015, Lisbon, Portugal (Hyun Jin Julie Yu, Nathalie Popiolek and Patrice Geoffron)

'**Solar Photovoltaic Energy Policy and Globalization**', *29th European PV Solar Energy Conference and Exhibition 2014*, 22-26 September 2014, Amsterdam, the Netherlands (Hyun Jin Julie Yu, Nathalie Popiolek and Patrice Geoffron)

'**Comparative Study on the Consequences and the Impacts of the Public Policies in favor of PV Development**', *19th International Energy Program Evaluation Conference*, 9-11 September 2014, Berlin, Germany (Hyun Jin Julie Yu, Nathalie Popiolek)

Seminars

'Economic Feasibility of PV Self-consumption in the French Residential Sector in 2030' (Poster), *Vers la transition énergétique - WTE 2016***,** *organized by L'université Paris-Saclay & la R&D du Groupe EDF***,** 4-5 October 2016, Palaiseau, France (submitted)

'**Solar Photovoltaic (PV) Energy Policies and Impacts on Technology Systems and Market Dynamics**' (Poster), *14e journées scientifiques de la DANS*, *CEA Saclay*, 19-20 May 2014, Gif sur Yvette, France (Hyun Jin Julie Yu)

'**South Korea's PV Policies**', *Les politiques publiques de l'énergie solaire, organized by Université de Savoie, EDF and INES,* 24 June 2013, Chambéry- le Bourget-du-Lac, France (Hyun Jin Julie Yu, Nathalie Popiolek)

Award

Student award winner, *29th European PV Solar Energy Conference and Exhibition 2014 (EU PVSEC)* September 22-26 2014, Amsterdam, the Netherlands

Annexes

Annex of Part I

1 Government's policies to promote renewable energies

	Stage	Method	Policy instruments	
Supply-side	R&D	Fiscal incentives	**Academic R&D funding:** investment to academic research **Grant:** funding for R&D and demonstration with no payment requirement **Incubation support:** assistance to entrepreneurs including business development and raising financing **National/ international public research center:** research facilities funded by local, national, international government bodies **Public –private partnership:** collaboration, techno, services, infra... **Prize:** award which allows the winner to finance private R&D **Tax credit:** full or partial deduction of tax obligation (e.g. income) **Voucher scheme:** to companies to access to R&D center	
	Demonstration	Fiscal incentives	**Grant:** funding for R&D and demonstration with no payment requirement	
		Public financing	**Venture capital**: from research to new products/services **Soft/convertible loan**: financing at pre-commercial stage to promote renewable energies	
	Pre-commercial	Public financing	**Venture capital**: from research to new products/services **Soft/convertible loan**: financing at pre-commercial stage to promote renewable energies	
Demand-side	Large-scale deployment	Fiscal incentives	**Grant:** monetary assistance which helps reduce investment costs in terms of preparation, buying and construction of renewable energy equipment and infra **Energy production payment**: direct payment to produce per unit of renewable energies **Rebate:** one-time direct payment from the government to a private party related to % of investment costs of RE system or service **Tax credit:** an annual income tax credit based on the amount of money invested in that facility or the amount of energy that it generates **Tax reduction/exemption:** reduction in tax—including but not limited to sales, value-added, energy or carbon tax—applicable to the purchase (or production) of RE or RE technologies **Variable or accelerated depreciation:** allow for reduction in tax burden in the 1st year of operation of RE equipment (commercial entities)	
		Public financing	**Investment:** Financing provided in return for an equity ownership interest in a RE company or project **Guarantee:** risk-sharing mechanism aimed at mobilizing domestic lending from commercial banks for RE companies and projects that have high perceived credit (i.e., repayment) risk **Loan:** financing provided to a RE company or project in return for a debt (repayment) obligation. Provided by government, development bank or investment authority usually on concessional terms (e.g., lower interest rates or with lower security requirements) **Public procurement:** public entities preferentially purchase RE services (such as electricity) and/or RE equipment.	
		Regulation	Quantity-driven	**Renewable Portfolio Standard (RPS)/ Quota obligation or mandate:** Obligates designated parties (generators, suppliers, consumers) to meet minimum (often gradually increasing) RE targets, generally expressed as percentages of total supplies or as an amount of RE capacity, with costs borne by consumers **Tendering/Bidding:** Public authorities organize tenders for given quota of RE supplies or supply capacities, and remunerate winning bids at prices mostly above standard market levels
			Price-driven	**Fixed payment feed-in-tariff (FIT):** guarantees RE supplies with priority access and dispatch, and sets a fixed price varying by technology per unit delivered during a specified number of years

				Premium payment FIT: guarantees RE supplies an additional payment on top of their energy market price or end-use value.
			Quality-driven	**Green energy purchasing**: regulates the supply of voluntary RE purchases by consumers, beyond existing RE obligations **Green labeling:** guarantees that energy products meet certain sustainability criteria to facilitate voluntary green energy purchasing
			Access	**Net metering:** allows a two-way flow of electricity between the electricity distribution grid and customers with their own generation. **Priority or guaranteed access to network:** provides RE supplies with unhindered access to established energy networks. **Priority dispatch:** mandates that RE supplies are integrated into energy systems before supplies from other sources

*Definition of policies in support of renewable energy development was adapted from IPCC special report (2011) and IRENA report (2012)

Annexes of Part II

1 PV demand: PV power production growth

Variable	Unit	Comment
Share of PV electricity	%	**Core variable: share of the PV electricity production in the domestic electricity consumption.**
Domestic demand	TWh	Domestic demand of electricity.
PV domestic production	TWh	Electricity generated by PV.
National average PV system Performance	kWh/kW	Average performance of the PV system. It depends on climate, geography, and the average efficiency of the PV system installed. The efficiency can be improved by technology-push policies.
PV installations	MWp	PV installed capacity; it can be constrained by network infrastructures, the flexibility of the electricity mix and the available surface to install the PV systems.
PV system demand	MWp	Demand in installing PV systems (incl. off-grid, residential, commercial, industrial, and utilities). It is Influenced by environmental consciousness (willingness to pay), access to finance, or demand-side policies (like RPS or positive energy buildings).
PV's rate of return (profitability)	%	Revenue vs. PV investment.
PV LCOE	$/MWh	PV Levelized Cost of Electricity (LCOE): PV power generation costs excluding grid-level costs and internalization of externalities. Government can internalize them through taxes on PV. The PV LCOE is largely influenced by demand-side policies (e.g. subsidies on PV investment).
PV electricity purchase price	$/MWh	Purchase price of the electricity generated by PV (e.g. FIT).
Retail electricity tariffs	$/MWh	This is regulated by policy maker, and related to energy equity.
Gross electricity price	$/MWh	It is related to industry competitiveness.
LCOE of competing energies	$/MWh	Other competing technologies' LCOE; it is influenced by energy policies (e.g. CO_2 pricing).
Fuel price	$/toe	Fuel costs (e.g. oil, coal, gas).
Economic growth	%	The economic growth increases the energy demand.

2 PV supply: economic growth through PV industry development

Variable	Unit	Comment
Economic growth	**%** **or** US$	**Core variable: PV sector's contribution to the national economic growth.** It can be affected by the cost of the PV policies (e.g. tax increase).
Electricity prices	$/MWh	The electricity prices influence the national economy. High electricity prices can reduce the industry competitiveness. The electricity prices can be changed to finance PV policies (e.g. EEG, CSPE).
Avoided energy importation	US$	Avoided energy importation induced by PV electricity production.
Additional energy importation	US$	Additional energy importation induced by PV electricity production (e.g. backup gas).
PV electricity production	GWh	The total production of PV electricity in the electricity system.
PV sector jobs	Number of jobs	PV jobs across the PV value chain (PV manufacturing and installations).
PV sector revenues	US$	Generated revenues by PV sector.
Related- industry revenues	US$	Generated revenues by related- industries (e.g. battery, building).
Domestic sales of PV industry	MWp or t	PV domestic production for the domestic demand.
Overseas sales of PV industry	MWp or t	Exportation of PV products.
PV system demand	MWp	Demand in installing PV systems (off-grid, residential, commercial, industrial, and utilities). It can be influenced by demand-side policies (like RPS or positive energy buildings) and the economic situation.
Domestic production costs	$/Wp	PV production costs by domestic firms: they can be influenced by technology skills and networks between industries, universities and research laboratories.
O&M	$/Wp	Operating and maintenance cost.
Wage	$/Wp	Salaries of employees.
Capital	$/Wp	Investment costs for construction of production capacity, they are influenced by the access to finance.
Global market price	$/Wp	Global selling prices of PV products.
Global PV production	GWp	Production volume of PV materials in the global market.

Energy price	$/toe	Energy prices used by the factories.
Currency exchange rate	1	The exchange rate of the domestic currency against foreign currencies. It influences the competitiveness of the domestic industry.
Global PV demand	MWp	Global demand in PV products. This can be influenced by economic situation.

3 PV integration: real costs of PV electricity in electricity mix

Variable	Unit	Comment
Real PV electricity cost	**$/MWh**	**Core variable: the real cost of PV power in the electricity system (PV generation costs + grid-level costs + externalities)**
Grid-level costs	$/MWh	Costs to strengthen the grid of transportation and distribution to integrate PV power in the electricity system. The grid upgrading costs include the costs related to grid reinforcement and extension.
Backup (long-term adequacy)	$/MWh	Additional costs to integrate PV: provision of dispatchable back-up capacity to satisfy electricity demand at any moment.
Balancing (short-term balancing)	$/MWh	Additional costs to integrate PV: second-by-second matching of electricity supply and demand.
Grid upgrading	$/MWh	Additional costs to integrate PV: grid reinforcement and extension.
Externalities	$/MWh	Externalities refer to positive or negative effects, which have not yet been internalized in the PV price.
Environment	$/MWh	Externalities on the environment (e.g. CO_2 emission reduction).
Electricity market	$/MWh	Externalities on the existing electricity mix (e.g. changes in the market price formation, de-optimization of the electricity mix).
Economic	$/MWh	Impacts on the economy.
PV LCOE	$/MWh	PV Levelized Cost of Electricity (LCOE).
Cost of capital	$/MWh	Financing costs to build or purchase assets. It includes the inflation and the interest rate for the use of money borrowed. It is considered as the WACC or the discount rate.
Land usage	$/MWh	Land use costs to install PV systems: this is constrained by available surfaces, urbanism rules and social acceptance.
O&M	$/MWh	Operating and maintenance cost.
PV system lifetime	Year	Lifetime of the PV system.
PV system performance	kWh/kW	PV electricity production vs. PV system capacity.
PV load factor	%	The ratio of its actual output over a period of time to its potential maximal output over the same period of time, and the lifespan of the plant. It is influenced by the geographic location.
PV system yield	%	Efficiency of the PV system (modules and all other components).
R&D production	Number of patents	R&D results to improve the PV sector (PV system yield, lifetime, and material usage).
PV system costs	$/Wp	Costs of each Wp installed.
Non-module hardware costs	$/Wp	This includes the supporting parts to mount modules (e.g. racking), the inverter to converts the DC power from the cells to AC power to be compatible with the electrical network, batteries, and other electrical devices (e.g. power control system, switchgear, fuses, cabling).
PV module costs	$/Wp	PV module costs.
Global production	GWp	Global accumulated production of PV modules. The accumulated experience reduces the price (learning curve effect).
Raw material quantity	g/Wp	Quantity of raw materials needed to produce PV cell/module.
Raw material prices	$/Wp	Cost of the raw materials needed to produce PV cell/module.
Soft costs	$/Wp	Soft costs cover any other services needed to design, install, and connect the PV systems to the network.
Installation	$/Wp	PV system installation cost.
Engineering	$/Wp	Engineering costs (e.g. PV system design).
Marketing	$/Wp	Costumer acquisition cost.
PII	$/Wp	Permitting, inspection and interconnection costs.
Seller profit	$/Wp	Profit and overhead of all the companies involved in the process.

Annexes of Part III

1 Calculations for the case study of PV self-consumption in French supermarkets

- PV electricity production by month

Unit:kWh/m^2	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Total**
PV production	**3.4**	**5.6**	**11.9**	**16.9**	**19.8**	**21.4**	**21.8**	**18.4**	**13.6**	**8.1**	**4.0**	**3.0**	**147.7**

- Electricity tariff decomposition by month

Unit: €/kWh	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Electricity Tariff	**0.09520**	**0.09520**	**0.09520**	**0.04990**	**0.04990**	**0.04990**	**0.04990**	**0.04990**	**0.04990**	**0.04990**	**0.09520**	**0.09520**
Electricity production	0.04760	0.04760	0.04760	0.02495	0.02495	0.02495	0.02495	0.02495	0.02495	0.02495	0.04760	0.04760
TURPE	0.04760	0.04760	0.04760	0.02495	0.02495	0.02495	0.02495	0.02495	0.02495	0.02495	0.04760	0.04760
CSPE	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950	0.01950
CTA	0.00375	0.00375	0.00375	0.00227	0.00227	0.00227	0.00227	0.00227	0.00227	0.00227	0.00375	0.00375
TCFE	0.00254	0.00254	0.00254	0.00154	0.00154	0.00154	0.00154	0.00154	0.00154	0.00154	0.00254	0.00254
TVA	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Total	**0.12101**	**0.12101**	**0.12101**	**0.07321**	**0.07321**	**0.07321**	**0.07321**	**0.07321**	**0.07321**	**0.07321**	**0.12101**	**0.12101**

The electricity consumption from the grid is reduced with the self-consumption of PV electricity. It induces stakeholders' losses as shown on the table below (PV production multiplied by the share of electricity tariff for each stakeholder concerned).

- Loss of each stakeholder because of reduced electricity purchase from the grid

Unit: €/m^2	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	Total
losses Producer	0.15998	0.26436	0.56720	0.42235	0.49455	0.53300	0.54315	0.45834	0.33843	0.20201	0.19000	0.14107	4.31445
losses TURPE	0.15998	0.26436	0.56720	0.42235	0.49455	0.53300	0.54315	0.45834	0.33843	0.20201	0.19000	0.14107	4.31445
losses CSPE	0.06554	0.10830	0.23236	0.33009	0.38652	0.41658	0.42450	0.35822	0.26450	0.15789	0.07784	0.05779	2.88013
losses CTA	0.01261	0.02083	0.04470	0.03842	0.04498	0.04848	0.04940	0.04169	0.03078	0.01837	0.01497	0.01112	0.37637
losses CTFE	0.00854	0.01411	0.03028	0.02602	0.03047	0.03284	0.03347	0.02824	0.02085	0.01245	0.01014	0.00753	0.25496
losses TVA	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Total of losses	**0.40671**	**0.67209**	**1.44198**	**1.23922**	**1.45108**	**1.56391**	**1.59367**	**1.34483**	**0.99300**	**0.59273**	**0.48304**	**0.35865**	**12.1409**

2 Data of countries with low electrification rates

The data have been compiled from the following sources:

- Inhabitants, electrification rates, inhabitants without electricity, and consumption per inhabitant: the World Bank[176].
- Solar PV resource:
  - PVgis[177] (free online software): for Africa countries based on default location of country and automatic optimal positioning of the PV panel.
  - NREL – PVWatts:[178] for non-African countries.

[176] http://donnees.banquemondiale.org/
[177] http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?map=africa&lang=fr
[178] http://pvwatts.nrel.gov/pvwatts.php

		Solar PV resources (kWh/kWp/year)	Inhabitants	Electrification rates (%)	Inhabitants without electricity	Electricity consumptions (kWh/inhab.)
Afghanistan	**AFG**	1590	31627506	43	18027678	
Angola	**ANG**	1630	24227524	37	15263340	220
Bangladesh	**BAN**	1400	159077513	59.6	64267315	279
Burkina Faso	**BUR**	1600	17589198	13.1	15285013	
Burundi	**BUR**	1440	10816860	6.5	10113764	
Cambodia	**CAM**	1460	15328136	31.1	10561086	207
Cameroon	**CAM**	1500	22773014	53.7	10543905	262
Central African Republic	**CAF**	1530	4804316	10.8	4285450	
Chad	**CHA**	1670	13587053	6.4	12717482	
Côte d'Ivoire	**IVO**	1420	22157107	55.8	9793441	240
Democratic Republic of the Congo	**DRC**	1350	74877030	16.4	62597197	105
Eritrea	**ERI**	1530	5110444	36.1	3265574	62
Ethiopia	**ETH**	1640	96958732	26.6	71167709	57
Ghana	**GHA**	1510	26786598	64.1	9616389	346
Guinea	**GUI**	1570	12275527	26.2	9059339	
Haïti	**HAI**	1538	10572029	37.9	6565230	50
India	**IND**	1550	1295291543	78.7	275897099	744
Kenya	**KEN**	1650	44863583	23	34544959	160
Laos	**LAO**	1270	6689300	70	2006790	
Lesotho	**LES**	1750	2109197	20.6	1674702	
Liberia	**LIB**	1400	4396554	9.8	3965692	
Madagascar	**MAD**	1710	23571713	15.4	19941669	
Malawi	**MAL**	1720	16695253	9.8	15059118	
Mali	**MAL**	1600	17086022	25.6	12712000	
Mauritania	**MAU**	1610	3969625	21.8	3104247	
Mozambique	**MOZ**	1510	27216276	20.2	21718588	444
Myanmar	**MYA**	1530	53437159	52.4	25436088	153
Namibia	**NAM**	1810	2402858	47.3	1266306	1591
Nepal	**NEP**	1190	28174724	76.3	6677410	119
Nicaragua	**NIC**	1389	6013913	77.9	1329075	580
Niger	**NGR**	1640	19113728	14.4	16361351	
Nigeria	**NIG**	1450	177475986	55.6	78799338	156
Papua-New-Guinea	**PAP**	1402	7463577	18.1	6112670	
Philippines	**PHI**	1188	99138690	87.5	12392336	672
Rwanda	**RWA**	1410	11341544	18	9300066	
Senegal	**SEN**	1610	14672557	56.5	6382562	210
Sierra Leone	**SIL**	1410	6315627	14.2	5418808	
Somalia	**SOM**	1670	10517569	32.7	7078324	
South Africa	**SAF**	1850	54001953	85.4	7884285	4405
South Sudan	**SSU**	1490	11911184	5.1	11303714	
Sri Lanka	**SRL**	1470	20639000	88.7	2332207	527
Sudan	**SUD**	1660	39350274	32.6	26522085	157
Swaziland	**SWA**	1500	1269112	42	736085	
Tanzania	**TAN**	1710	51822621	15.3	43893760	99
Togo	**TOG**	1490	7115163	31.5	4873887	145

Uganda	**UGA**	1550	37782971	18.2	30906470	
Yemen	**YEM**	1850	26183676	48.4	13510777	170
Zambia	**ZAM**	1680	15721343	22.1	12246926	571
Zimbabwe	**ZIM**	1730	15245855	40.5	9071284	562

Les politiques de développement du solaire photovoltaïque et leurs impacts sur les dynamiques des technologies et des marchés

Hyun Jin Julie YU

Résumé étendu

1 Contexte

La prise de conscience croissante des questions environnementales a accru l'intérêt porté aux énergies renouvelables dont l'énergie solaire. Ces dernières décennies, le changement climatique a été l'objet d'importantes négociations internationales. L'accord de Paris (2015) a pris des mesures supplémentaires pour encadrer les efforts internationaux visant à réduire les causes et les impacts du changement climatique. L'énergie solaire photovoltaïque (PV) a attiré l'attention de nombreux gouvernements en étant l'une des technologies favorites pour la transition énergétique bas carbone dans la communauté mondiale.

Les ressources solaires sont disponibles partout sans risque de conflit géopolitique sur les ressources naturelles. En outre, l'énergie PV induit peu de risques technologiques et offre la possibilité d'être décentralisée. Sur la base de ces avantages, le marché des systèmes PV a connu une forte croissance cette dernière décennie soutenue par des actions politiques favorables dans un contexte de transition énergétique. Le coût des modules PV a été fortement réduit passant d'environ 4.5 \$/Wp en 2005 à 0.61 \$/Wp en 2015. Ainsi, le LCOE de la plus compétitive des grandes centrales solaires a chuté de plus de 350\$/MWh en 2005 à environ 80\$/MWh en 2014. Les installations cumulées mondiales sont passées de 1.2 GWp en 2000 à 178 GWp en 2014. Pourtant, malgré ces conditions bénéfiques, le marché mondial du PV a paradoxalement traversé une période chaotique rencontrant des problèmes de surproduction, une crise industrielle avec la faillite de nombreuses entreprises et des différends commerciaux durables entre pays. Par ailleurs, alors que le niveau de pénétration du PV dans le mix augmente, plusieurs problématiques ayant un impact négatif sur le secteur de l'électricité ont commencé à apparaitre. Ce constat commence à être visible en Allemagne qui a le plus haut niveau de pénétration du PV dans le mix électrique. Cette thèse part de ces problématiques.

La majorité des recherches existantes sur le secteur PV utilise un angle d'étude adapté à une question spécifique et ces recherches peuvent suivre des orientations très diverses vus les nombreux sujets d'intérêt liés au secteur. Cependant, les décideurs politiques ont également besoin d'un point de vue plus holistique pour décider des orientations stratégiques pour le développement du PV dans le futur système énergétique. En complément des recherches qui se focalisent sur des questions précises, la thèse propose donc une approche plus systémique offrant un point de vue plus large sur le sujet permettant d'analyser le système des politiques PV et sa dynamique dans son ensemble. L'étude du système des politiques PV s'effectue en intégrant la mondialisation du secteur afin de mettre en évidence la dynamique du système au niveau international.

2 Méthodologie : une approche systémique

La thèse tente de répondre aux questions de recherche suivantes :

1) Quels sont le contexte et les variables clés associés au développement du PV et aux politiques qui l'accompagnent ?
2) Quels sont les défis et les limites critiques liés aux politiques PV et quels mécanismes existent derrière eux ?

Une fois les mécanismes du développement du PV identifiés avec les limites et défis critiques, la thèse tente de répondre à une troisième question :

3) En prenant en compte les limites et défis critiques actuels, quelles orientations stratégiques peuvent améliorer les mécanismes des politiques PV ?

Il n'est possible de répondre à ces questions qu'en adoptant une approche systémique sous un contexte dynamique permettant d'avoir une compréhension juste et complète des mécanismes des politiques publiques PV. La façon de gérer les risques connus ou inconnus liés au développement du PV dans le mix énergétique est essentielle au succès des politiques PV. Les décideurs politiques du monde entier aspirent à anticiper correctement toute menace politique afin d'éviter les conséquences négatives. Cela peut ressembler à un jeu de hasard, mais une approche stratégique est possible pour gérer ce genre de situation. Cela peut être fait en combinant deux techniques :

- Modéliser le système du PV en prenant en compte autant de facteurs d'influence que possible afin de donner une vision d'ensemble précise du système (approche systémique).
- Construire des outils de connaissance robustes pour anticiper les changements en rupture sur le marché du PV et l'apparition de nouveaux modèles de business; ces outils peuvent être construits sur la base d'expériences partageant des similarités (analyse rétrospective).

A cet égard, nous avons décidé d'analyser les problématiques sur la base de ces techniques. Le but de cette approche est d'exposer les mécanismes concrets en œuvre sous les politiques PV en prenant en compte leur complexité et leur caractéristique dynamique. L'analyse systémique nécessite d'élargir le champ d'étude pour comprendre chaque segment du système et pour mettre en évidence les liens entre ces segments généralement étudiés séparément. L'étude tente d'intégrer la plupart des domaines d'intérêt qui influencent les mécanismes des politiques PV. Cela implique l'utilisation d'outils d'analyse appropriés à chaque secteur étudié. L'étude est ainsi conduite en trois temps :

1) Faire une analyse théorique permettant de définir le contexte des politiques publiques PV.
2) Faire une analyse rétrospective permettant de comprendre les facteurs de risque critiques dans les mécanismes des politiques PV.
3) Proposer des orientations stratégiques pour les politiques publiques PV.

La structure de cette thèse suit cet ordre logique et se repose sur trois parties.

1) **Partie I : Analyse théorique définissant le contexte des politiques publiques en soutien à l'énergie PV**

La partie I s'intéresse aux politiques publiques (chapitre 1) et aux technologies PV avec leur coût et leurs usages en incluant l'intégration dans le mix électrique (chapitre 2). Une fois le contexte correctement défini, nous comprenons que le développement du PV est limité sans cadre politique. Le chapitre 3 présente donc le rôle des politiques publiques pour le développement de l'énergie PV avec un focus sur les scénarios de l'IEA et ses suggestions politiques pour les suivre. Ensuite, une analyse de risque est conduite pour identifier les risques et défis les plus importants sur le développement de l'énergie PV dans les systèmes énergétiques actuels et futurs. La Partie I offre la base théorique pour les parties II et III plus appliquées.

2) **Partie II : Analyse rétrospective pour comprendre les défis et risques critiques des politiques PV**

Dans la partie II, une analyse rétrospective des politiques PV dans les principaux pays du secteur est conduite. Le chapitre 1 propose une vue générale des tendances du marché du PV ainsi que du contexte. L'objectif du chapitre est de définir les principaux acteurs du secteur PV, à la fois pour l'offre et pour la demande, afin de sélectionner les pays qui seront étudiés en détail dans l'analyse rétrospective. Dans le chapitre 2, l'analyse rétrospective est conduite en utilisant un graphe schématique des mécanismes des politiques PV. L'Allemagne, le Japon et la Chine sont principalement ciblés du fait de leur position historique importante sur l'offre et la demande mondiale. La France, les Etats-Unis et la Corée sont également étudiés du fait de leur position visible sur le marché du PV et de leurs politiques PV particulières. Dans le chapitre 3, nous proposons des visions détaillées sous forme de mapping de variables sur trois piliers importants des politiques PV : la croissance de la production d'énergie PV, les bénéfices économiques résultant du développement de l'industrie PV et la réduction des coûts de l'électricité PV. L'analyse systémique sur la base de ces mappings conduit à s'intéresser à la dynamique des politiques PV. Ainsi, la partie se conclut en présentant les défis et risques critiques des politiques PV qui ont émergé dans les principaux pays du secteur du fait de l'aspect dynamique du système.

3) **Partie III : Propositions d'orientations stratégiques pour les politiques PV pour d'avantage de croissance**

Dans la partie III, des orientations stratégiques pour le développement du PV sont proposées. Nous discutons tout d'abord du nouveau mode d'utilisation du PV avec l'autoconsommation. Les notions de base liées à l'autoconsommation sont d'abord introduites puis une analyse des acteurs est présentée afin d'identifier les parties prenantes de l'intégration du PV dans le mix électrique. Ensuite, une étude micro-économique est menée pour évaluer l'opportunité offerte par l'autoconsommation PV dans les supermarchés en France. Cette étude de cas a pour objectif d'analyser les effets du modèle d'autoconsommation de l'énergie PV et d'exposer en quoi ce modèle répond à certaines questions levées précédemment. Cette étude est ensuite étendue à plus long terme en s'intéressant au secteur résidentiel avec l'utilisation de systèmes PV associés à des batteries Lithium-Ion. Dans le chapitre 2, nous tentons de donner une vision précise des effets de la mondialisation sur les mécanismes des politiques PV en nous basant sur l'étude parallèle de l'Allemagne et de la Chine. Notre étude cherche à expliquer en quoi la politique de commerce stratégique du gouvernement chinois a influencé les choix d'investissement et les revenus des acteurs du marché. Nous nous appuyons pour cela sur les caractéristiques du marché mondial du PV qui sont essentielles pour comprendre le contexte des mouvements stratégiques de la Chine et ses conséquences. Nous suggérons également une nouvelle configuration du jeu pour trouver des possibilités d'accroissement des bénéfices pour les acteurs du marché dans le futur. Dans le chapitre 3, nous proposons ainsi des solutions pour sortir de la crise mondiale du secteur sur la base d'une coopération internationale. L'opportunité offerte par l'électrification dans les pays en voie de développement est quantifiée ainsi que l'impact que cela pourrait avoir sur le secteur PV au niveau mondial. Pour terminer, nous proposons des actions politiques en coopération permettant d'accroitre la compétitivité des systèmes PV en diminuant les coûts hors-module.

3 Résultats

Cette thèse a défini les variables clés associées au développement du PV et mis en évidence son contexte dynamique. Elle a analysé les limites et défis critiques liés aux politiques PV et aux mécanismes sous-jacents. La thèse fournit une vue d'ensemble des mécanismes des politiques PV incluant toutes les variables pertinentes et les acteurs et intégrant leurs propriétés dynamiques. Ensuite, cette thèse a proposé des orientations stratégiques pour améliorer le développement du secteur PV dans le futur selon deux dimensions, l'une nationale avec un mode approprié d'utilisation de l'énergie PV et l'autre international avec des opportunités pour sortir de la crise industrielle mondiale. L'approche systémique et les méthodologies proposées dans la thèse pourraient être utiles pour tous les acteurs engagés dans les politiques PV. Les principales conclusions et contributions sont présentées ci-dessous selon l'ordre des parties de la thèse.

3.1 Partie I: Une vision systémique des mécanismes des politiques PV

Comparée à la plupart des études existantes sur le sujet, cette thèse présente une vision systémique de l'évolution du secteur PV englobant les secteurs pertinents côté offre et coté demande, le contexte politique et la dynamique de changement.

La partie 1 a présenté les objectifs politiques qui motivent la mise en place de politiques PV dont notamment la transition énergétique et le développement économique durable (croissance verte). L'état de l'art des technologies PV montre que la technologie au silicium cristallin domine largement le marché, créant probablement un verrouillage du marché qui bloque l'émergence des autres technologies pouvant présenter de l'intérêt sur d'autres usages.

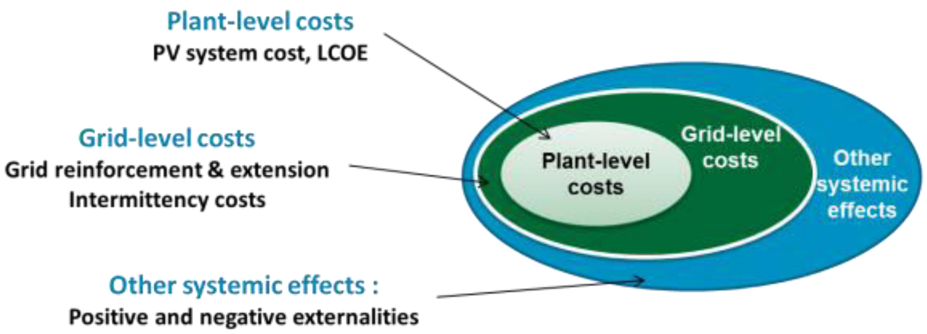

Figure 1: Coût total du système PV (OECD/NEA)

En parallèle des bénéfices du développement de l'énergie PV pour la société, la partie insiste également sur la complexité de la gestion du système électrique. Le développement de la production d'électricité PV induit des impacts systémiques à la fois sur la gestion du réseau et sur les acteurs conventionnels du secteur. Enfin, une analyse SWOT des différents usages du PV fait ressortir différentes options pour utiliser de manière optimale l'énergie PV. Ces options dépendent du contexte régional et elles sont différentes dans chaque pays ou chaque région.

3.2 Partie II: Analyse rétrospective, mappings et problématiques critiques

La partie II propose deux types de mapping aidant à la mise en place et au contrôle des politiques publiques PV. Le premier mapping offre une vision générale macroscopique avec une synthèse claire du système politique reliant les objectifs politiques aux résultats.

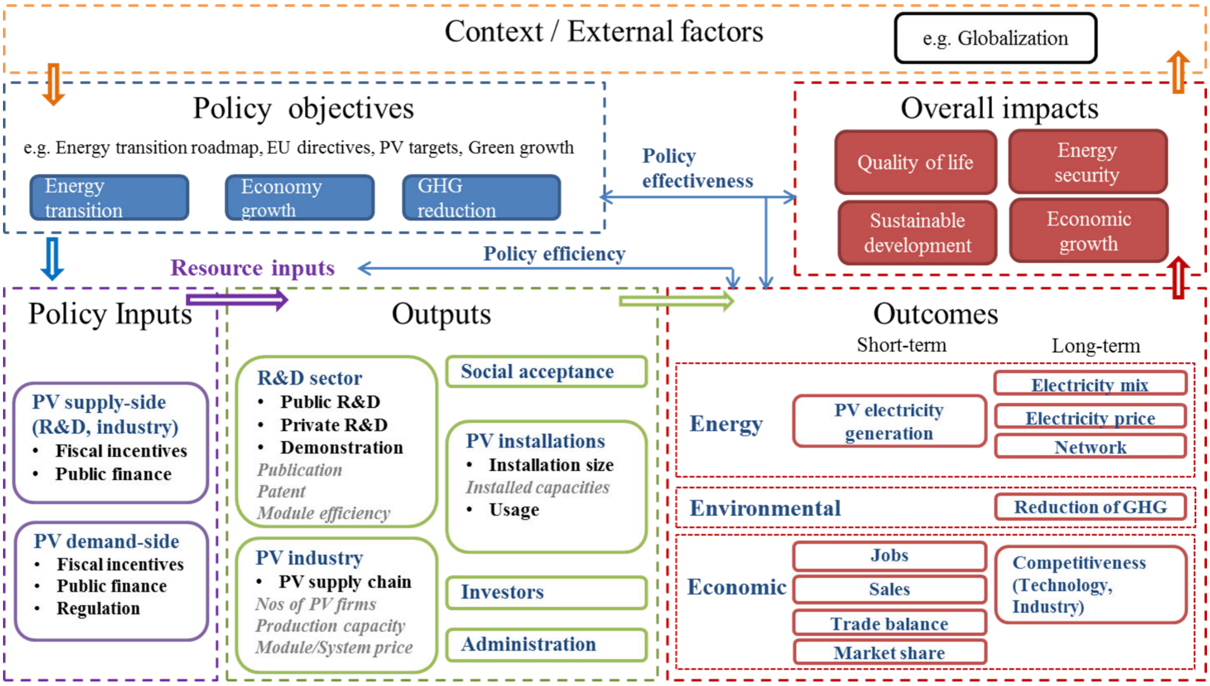

Figure 2: graphe schématique des mécanismes des politiques publiques PV (proposé par l'auteur)

Ce mapping a permis de conduire l'analyse rétrospective comparative de 6 pays (Allemagne, Japon, Chine, USA, France et Corée du Sud) sur la base d'une méthodologie commune. Cette analyse a mis en évidence la diversité des politiques publiques PV ainsi que leur caractéristique dynamique. La continuité des politiques PV lors de ces dernières décennies a été un facteur important qui a conduit l'Allemagne et le Japon à devenir des pays leaders, contrairement à la France et aux USA pourtant pionniers du secteur. Ces politiques ont conduit à une forte augmentation des installations dans ces pays et ont créé de nombreux emplois jusqu'à la fin des années 2000.

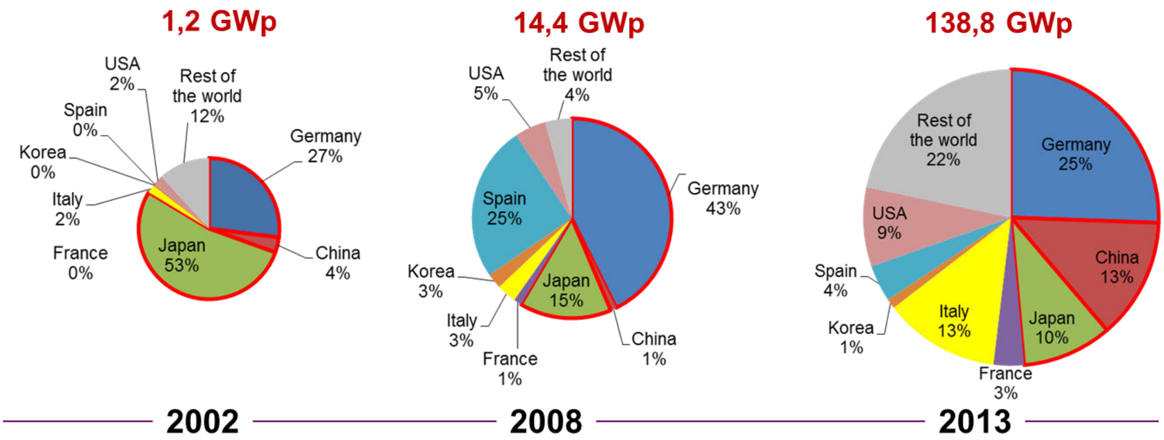

Figure 3: Installations cumulées de capacités PV dans le monde

Cependant, le contexte a changé ces dernières années avec la mondialisation et la crise économique. L'Europe s'est surtout concentrée sur la transition énergétique mais a essayé de mettre en place un mix équilibré entre politique de l'offre et politique de la demande. En revanche, plusieurs pays asiatiques se sont principalement concentrés sur la production. Les effets d'échelle sont devenus un critère important de la baisse des prix du PV et l'entrée de la Chine sur le marché mondial avec sa politique de l'offre a déstabilisé le secteur.

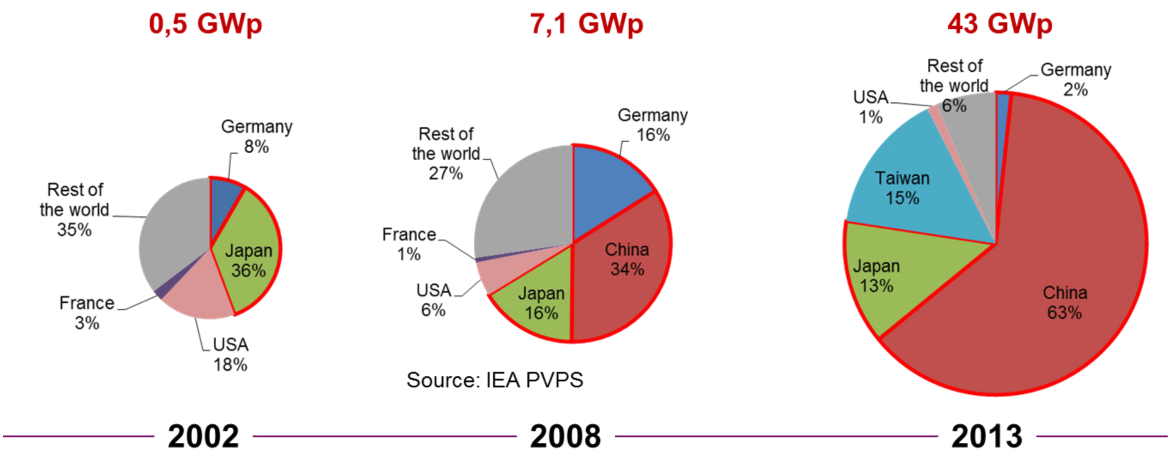

Figure 4: Production annuelle de cellules PV dans le monde

Les pays ayant choisi les Feed-in-Tariff (FIT) pour soutenir la demande PV ont connu des pics d'installations entrainant de fortes augmentations des coûts de leur politique (principalement payés par les consommateurs d'électricité) et la Chine a connu au final une crise de surproduction lorsque le marché européen a ralenti.

L'analyse rétrospective basée sur le mapping macroscopique nous a permis d'isoler trois variables cœur : la croissance de la production d'énergie PV, la croissance économique au travers du développement du secteur PV et la compétitivité de l'électricité PV. Autour de chaque variable cœur, un mapping détaillé a été construit à partir de variables mesurables. Ces mappings nous donnent la possibilité de décomposer les mécanismes des politiques PV et nous permettent de comprendre les impacts des politiques publiques pour le PV, de mesurer leur efficacité et d'identifier les endroits où les problèmes apparaissent.

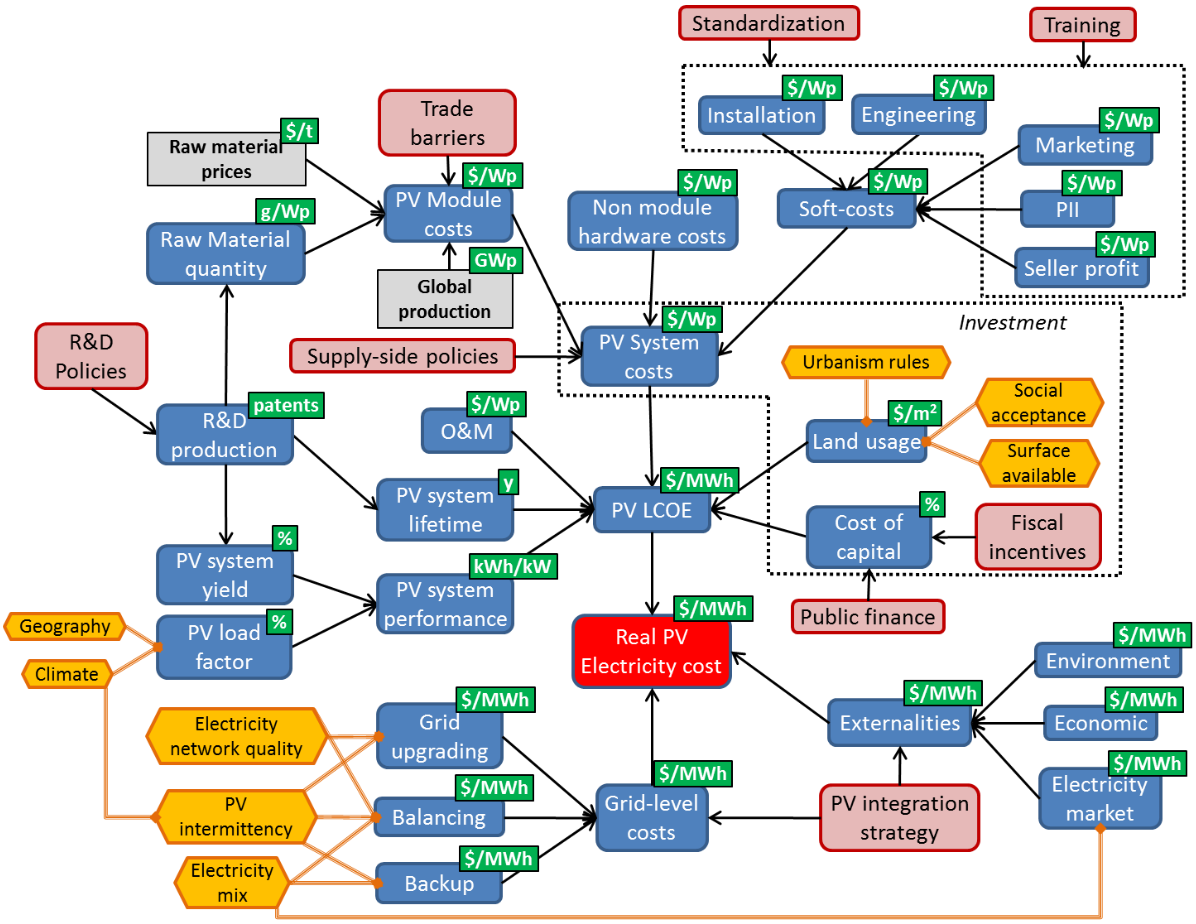

Figure 5: Exemple de mapping détaillé: L'intégration du PV dans le mix et le coût réel de l'électricité PV ($/kW)

Sur la base de ces mappings, trois problématiques critiques relatives aux mécanismes des politiques PV et liées à la dynamique du système ont été levées : l'efficacité du FIT pour stimuler la demande, l'impact de l'intégration du PV sur le système électrique et l'influence de la mondialisation du secteur PV. La thèse montre que le FIT est un système très sensible et a eu des conséquences inattendus du fait des changements rapides du marché du PV. Ce mécanisme a provoqué des pics incontrôlés d'installations dans la plupart des pays étudiés augmentant le cout des politiques et impactant récemment le marché de l'électricité.

L'étude met également en évidence l'impact systémique du solaire PV sur le système électrique, même si cet impact est difficilement mesurable du fait du contexte compliqué dans lequel se trouve le secteur de l'électricité avec la sortie du nucléaire dans certains pays et la chute des prix des matières premières. Des stratégies doivent être mises en place pour limiter ces impacts.

Pour terminer, nous avons insisté sur la nécessité d'intégrer la dynamique du contexte international lors de la conception de politiques nationales. Le système des politiques PV est devenu plus complexe avec la mondialisation du secteur. Les interactions entre les politiques publiques PV de différents pays ont eu des effets négatifs en brisant l'équilibre mondial du marché PV.

3.3 Partie III : Autoconsommation, politique de relance internationale

Avec la mondialisation du marché, l'énergie PV a beaucoup gagné en compétitivité ces dernières années. Cette baisse rapide du prix des systèmes PV commence à rendre l'autoconsommation PV attractive pour les consommateurs d'électricité. Cependant, cette amélioration de la compétitivité du système PV lève de nouvelles questions pour le décideur politique concernant le mix électrique optimal et le financement du réseau qui permettent d'assurer l'équilibre offre-demande d'électricité. L'objectif de la thèse a alors été de fournir au décideur politique les éléments nécessaires pour préparer une politique publique PV plus efficace pour le futur. Afin de développer le modèle d'autoconsommation PV, notre étude a montré l'intérêt de donner la priorité aux secteurs garantissant une consommation à 100% sur site comme les supermarchés. La surface disponible sur les supermarchés en France représente un potentiel d'installations d'environ 2.6 GWp. L'étude indique que l'autoconsommation à 100%, se basant sur des systèmes PV distribués et évitant les injections sur le réseau, permettrait de réduire les surcoûts sur le réseau. La réduction est de l'ordre de 30% à 10% de pénétration PV en France par rapport aux grandes centrales PV au sol. Comparé au FIT, l'autoconsommation à 100% s'avère également plus économique et permettrait d'éviter les effets d'aubaine. Avec la baisse des prix des systèmes PV et des batteries, cette approche peut être étendue dans le futur aux secteurs présentant des profils de consommation d'électricité moins adaptés à la production PV comme le résidentiel. Sur la base des scénarios IEA, l'étude indique que les systèmes avec batterie deviendraient rentables avant 2030 en France.

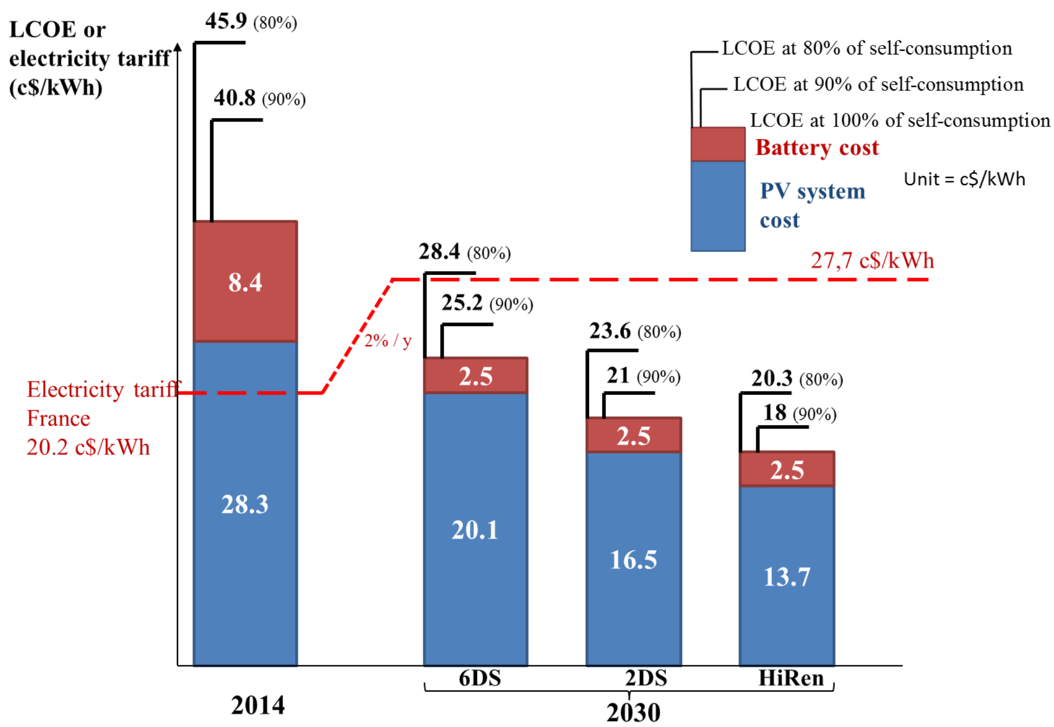

Figure 6 : Attrait économique de l'autoconsommation PV avec batterie dans le résidentiel en 2030

Cela représente 56 GWp d'installations potentielles produisant environ 12% de la consommation d'électricité nationale si toutes les maisons individuelles passaient à l'autoconsommation 100%. Si les décideurs politiques choisissent de promouvoir ce modèle et souhaitent atteindre la rentabilité plus tôt, la thèse montre que des gains significatifs sont possibles sur les coûts hors modules en France. Ce mode de consommation devrait induire des changements organisationnels et faire apparaitre de nouveaux modèles de business. Pour autant, l'étude présente également les coûts indirects d'une telle politique notamment les pertes pour l'opérateur réseau, critiques quant à la sécurité du système électrique. Ces pertes pour les acteurs traditionnels sont liées à la baisse de consommation depuis le réseau et peuvent être mesurées en se basant sur les tarifs de l'électricité. Les gouvernements doivent dès à présent se préparer en définissant des politiques d'atténuation des risques en ciblant le groupe d'acteurs le plus influent (opérateurs réseau, producteurs conventionnels et consommateurs). Dans l'objectif de se préparer à l'arrivée de la demande naturelle pour l'autoconsommation PV, nous recommandons de préparer une politique de transition régulière et progressive. Elle doit donner suffisamment de temps aux producteurs traditionnels pour s'adapter à la nouvelle situation de marché, fournir aux entreprises et investisseurs du secteur PV un signal politique stable et long terme et permettre de limiter les impacts négatifs sur le mix électrique en s'adaptant par exemple à l'âge des capacités de production en cours d'utilisation. En ce sens, la thèse prévoit un passage progressif des politiques en faveur de la croissance du PV vers des politiques de régulation permettant de contrôler l'impact systémique de l'intégration du PV dans le système électrique. Cela devrait éviter une diffusion chaotique de l'autoconsommation dans le futur.

Pour terminer, la thèse propose une voie pour échapper à la situation de crise actuelle de l'industrie PV. Il a été montré les difficultés pour implémenter une politique PV du fait de la complexité et de la dynamique du système. Nous avons montré l'importance d'une croissance régulière de la demande avec un signal politique stable et de long terme permettant entre autre de stabiliser l'emploi sur le secteur. Cependant, les politiques nationales ont leurs limites et la croissance de la demande nationale pourrait être insuffisante pour soutenir une industrie mondialisée qui a investi dans des usines de taille GW. A cet égard, afin de résoudre la crise industrielle, il est possible d'étendre la portée des stratégies politiques en stimulant la demande au niveau international.

En échange d'un arrêt des subventions de la Chine à son industrie, il est proposé de définir une politique internationale préparant des actions collaboratives pour offrir de nouveaux débouchés à la surproduction PV. Sur ce principe, l'amélioration de l'accès à l'électricité dans les pays en développement en utilisant des systèmes PV hors-réseau a été étudiée dans la thèse. Ce problème concerne environ 1.3 milliard de personnes et cette politique pourrait fournir un modèle socio-économique de développement dans les régions pauvres du monde. Cette opportunité permettrait de répondre à plusieurs sources mondiales d'inquiétude. Elle réduirait les émissions mondiales de CO_2 comparées à un développement sans action, elle fournirait un moteur pour la croissance de l'industrie du secteur PV et permettrait le développement durable des pays en développement en augmentant leur accès à l'électricité. La stratégie domino de diffusion du PV proposée dans la thèse permettrait d'améliorer l'efficacité de la politique en réduisant son coût. Cette stratégie donne la priorité aux pays les plus ensoleillés qui ont le coût le plus bas du PV avant de passer aux autres pays avec moins de ressources solaires. Elle tire ainsi profit de la dynamique baissière des coûts du PV liée à l'effet d'apprentissage. Le PV améliorerait au final sa compétitivité en bénéficiant de l'accroissement important du marché ce qui permettrait d'accroitre les installations PV des pays développés à un coût plus faible. L'ensemble des acteurs serait gagnant sur le long terme au regard de leurs objectifs politiques (industrie ou transition énergétique). Au final, un cercle vertueux sur le secteur PV, comme observé au début des années 2000 au niveau national, est reproduit mais cette fois à une échelle mondiale.

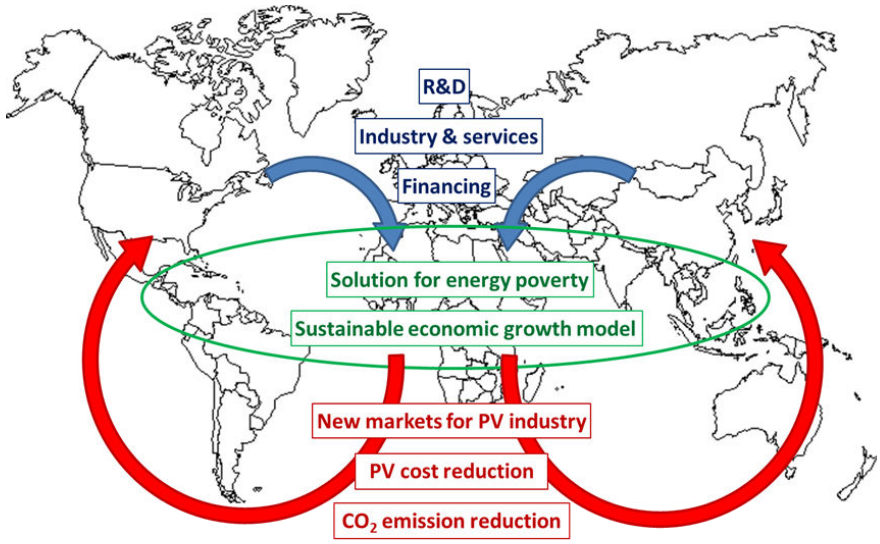

Figure 7: « Cercle vertueux » mondial sur le secteur PV (proposition de l'auteur)

4 Conclusion

La thèse comporte des analyses du secteur PV sur plusieurs périodes de temps pour mettre en évidence la dynamique des mécanismes des politiques publiques nationales. Le principe de « cercle vertueux » décrit par Watanabe en 2000 était applicable au niveau national jusqu'au milieu des années 2000, pour peu que la politique soit suffisamment ambitieuse et stable sur le long terme. Cependant, nous avons montré que la dynamique nationale a été brisée par l'entrée de la Chine sur le marché PV sur la base d'une analyse croisée de différents pays mettant en évidence les interactions entre les différentes stratégies politiques.

Avec un marché PV mondialisé, le prix des systèmes PV a été largement réduit ces dernières années. La diminution rapide des prix des systèmes PV rend l'autoconsommation PV de plus en plus attirante selon les régions. La thèse a démontré que l'autoconsommation PV à 100% est une solution plus économique que le financement par les FIT et minimise les effets systémiques par rapport à de grands systèmes PV centralisés connectés au réseau. Cependant, il devient également nécessaire de penser aux impacts indirects sur les acteurs, en particulier le gestionnaire de réseau. A cet égard, la thèse prévoit **un passage progressif d'une politique de soutien à la croissance du PV vers une politique de régulation pour limiter les impacts systémiques de l'intégration du PV dans le système électrique**. Les politiques PV futures devraient donc se concevoir sur la base de la vision systémique proposée dans la thèse intégrant le secteur électrique dans son ensemble, tout en permettant à l'industrie PV de se développer dans la perspective de sa participation au marché mondial.

En outre, la thèse propose une solution de développement du marché mondial aux travers d'actions internationales collaboratives afin d'offrir de nouveaux débouchés pour la production mondiale excédentaire. Cela contribuerait à réduire les émissions mondiales de CO_2 par rapport à un développement sans action correctrice, à apporter un nouveau moteur de croissance à l'industrie PV mondiale et finalement, à mettre en place un modèle de développement durable dans les pays en développement en augmentant l'accès à l'électricité. L'ensemble des acteurs devrait bénéficier au final de ce développement quel que soit leur objectif politique (industrie ou transition énergétique). En résumé, cela produirait un **« cercle vertueux » dans le secteur PV mais, cette fois, à l'échelle mondiale**.

Résumé

Cette thèse tente de comprendre les politiques publiques PV et les impacts sur la dynamique des technologies et des marchés. Une approche systémique est utilisée pour donner une compréhension précise des mécanismes des politiques publiques PV. Une analyse rétrospective, utilisant des mappings incluant les variables clés et le contexte, est conduite afin de cerner les limites et défis critiques du développement du PV. Cette thèse montre également la façon dont la nature du contexte politique change en lien avec la dynamique du secteur PV. Elle fait apparaître que la dynamique nationale a été brisée par l'entrée de la Chine. La thèse propose au final des orientations stratégiques nationales et internationales pour le développement du PV. Au niveau national, la thèse s'intéresse à l'autoconsommation PV, manière naturelle d'utiliser l'énergie PV dans le système électrique. Elle indique un possible changement de nature des politiques PV dans le futur. Afin de résoudre la crise industrielle mondiale, la thèse présente des possibilités d'actions internationales pour dynamiser la demande mondiale en recherchant des bénéfices économiques et environnementaux.

Abstract

This thesis attempts to understand PV public policies and the impacts on dynamics of technology systems and markets. A systemic approach is taken to provide an accurate comprehension of the mechanisms of PV public policies. A retrospective analysis using the proposed mapping tools that include key variables and the context is conducted to understand critical limits and risks of PV development. The thesis also demonstrates how the nature of policy context changes in combined with dynamic features of PV sector. It highlights nationwide PV policy dynamics was broken with the arrival of China. This thesis eventually proposes strategic orientations of PV development at the two dimensions from both national and international perspectives. At the national level, this thesis discusses on PV self-consumption as the natural way of PV power use in the electricity system. It indicates a possible change in the nature of PV policies in the future. As a response to the global industry crisis, the thesis proposes opportunities of international collaborative actions to create new PV demand in the international context in pursuit of global economic and environmental benefits.

Mots Clés

Mondialisation, Dynamiques de marché, Analyse prospective, Intégration PV, Mécanismes de politique PV, Autoconsommation PV, Énergies solaires, Économie du solaire PV, Commerce stratégique, Approche systémique

Keywords

Globalization, Market dynamics, Prospective analysis, PV integration, PV policy mechanisms, PV self-consumption, Solar energies, Solar PV economics, Strategic trade theory, Systemic approach