



LUND UNIVERSITY

A framework for analyzing deployment of solar photovoltaics, with a focus on building-sited grid-connected systems

Palm, Alvar; Neij, Lena

2012

[Link to publication](#)

Citation for published version (APA):

Palm, A., & Neij, L. (2012). *A framework for analyzing deployment of solar photovoltaics, with a focus on building-sited grid-connected systems*. Paper presented at IST 2012 - International Conference on Sustainability Transitions.

Total number of authors:

2

General rights

Unless other specific re-use rights are stated the following general rights apply:

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

Read more about Creative commons licenses: <https://creativecommons.org/licenses/>

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00

A framework for analyzing deployment of solar photovoltaics, with a focus on building-sited grid-connected systems

Alvar Palm and Lena Neij, IIIIEE, Lund University, Sweden.

Abstract

Policy intervention schemes for increased deployment of solar photovoltaics (PV) have been launched in several countries, with varying success. In order to ensure an efficient deployment of the technology, thorough knowledge is needed about relevant present actors and institutions, and about how a desirable actor base and institutional setup should look like; mere cost reductions are not enough to guarantee deployment of a new technology. A framework that captures the systemic nature of technical change, i.e. the development and deployment of new technology, is the technological innovation systems (TIS) framework. The objective of this paper is to discuss how the TIS framework could be used to analyze policy for PV with a focus on deployment of grid-connected, building-sited PV systems. So far, little emphasis has been on using TIS for detailed analysis of deployment of new emerging energy technologies. The TIS framework has been used for analyzing market growth of new energy technologies including processes of deployment in parallel with processes of technology development and production. We argue that “upstream” parts of the PV value chain differ fundamentally from “downstream” parts in that “upstream” activities (e.g. production of purified silicon, wafers, and solar cells) can often be understood as pertaining to a global TIS, while “downstream” activities (system installation etc.) could generally be assumed to be part of a more local (or national) TIS, and we identify and discuss components and processes of the TIS that are of particular importance for deployment of PV.

1. Introduction

The installed global capacity for solar photovoltaic (PV) electricity generation has increased at an exponential rate over the last decades, and has by now exceeded 50 GW_p (EurObserv'ER, 2012). Meanwhile, the prizes of PV systems have fallen dramatically. Germany and Italy are world leaders in terms of installed capacity for solar electricity generation, in total figures as well as per capita (EurObserv'ER, 2012). The massive deployment of the technology in these and other countries has been utterly dependent on financial supporting schemes (Dusonchet and Telaretti, 2010; Dewald and Truffer, 2011). Apart from directly stimulating demand through guaranteeing an above market price for PV electricity or subsidizing investments in PV systems, such schemes have enabled learning processes in the industry by creating markets for the technology, which has led to substantial cost reductions for PV systems – and in turn to more installed capacity (IEA, 2012). PV electricity is expected to reach grid parity (i.e. become as cheap as electricity bought from the grid) in a number of regions within a few years (EurObserv'ER, 2012; EPIA, 2011). Grid parity, however, will not necessarily lead to immediate commercial competitiveness; high upfront costs and presumed hassle might deter potential users (Yang, 2010), a maladapted institutional set-up might hamper technology diffusion in various ways (e.g. Unruh, 2000), and a lack of knowledge among relevant actors (or a lack of actors) may hinder deployment. While neoclassical analysis may be used to find business models to cope with potential

users' unwillingness to pay high upfront costs – for example through third-party ownership – a broader perspective is needed to tackle issues like institutional change and processes of learning; the process of deployment of PV systems is complex, and various actors with different kinds of knowledge need to participate, including installers, roofers, electricians, and grid regulatory authorities. Systems are needed for development and exchange of knowledge, and rules are needed to guarantee quality and safety, etc.

PV installation accounts for a significant portion of the cost for a turn-key system. The cost dynamics of PV deployment – and the potential for cost reductions – rely on site-specific conditions and learning that will, to a large extent, be local in nature. In order to obtain reduced costs related to deployment, learning that is more local than learning related to development and production of PV technology is needed. To support learning leading to cost reductions related to deployment, good knowledge about the PV innovation system is required, with a focus on deployment.

A framework that captures aspects of technological change that are relevant for policy makers is the technological innovation systems (TIS) framework (e.g. Bergek et al., 2008a; Hekkert et al., 2007). In this paper, we elaborate on how the TIS framework could be used to study deployment of *building-sited, grid-connected* PV systems. The focus on deployment – i.e. the process in which the technology is put into use – means that earlier parts of the value chain, such as solar cell development and PV module manufacturing, are not at focus.

Even though our framework is developed specifically for the PV technology, it is hoped that it might provide insights useful for analyzing the deployment of other technologies as well.

2. Theoretical background: innovation systems

A systems approach is often perceived as appropriate to understand processes of innovation. The neoclassical approach, assuming a static context and adopting a rather narrow focus, does not deal in a satisfactory way with such critical aspects of the economic system as learning and innovation (Lundvall, 1992). As a response to this insight, the concept of 'innovation systems' has been developed and refined over the last decades to capture the dynamics of socio-technical change. The concept, focusing on the importance for technological change not only of firms and research institutes but also of a larger societal context, has been developed mainly by "economists and other scholars of technological advance who adhere to an evolutionary theory of economic growth" (Nelson and Nelson, 2002).

A system can be generally defined as "a group of components (devices, objects or agents) serving a common purpose, i.e. working towards a common objective or overall function", but even though "the system concept may suggest collective and coordinated action, an innovation system is primarily an analytical construct" (Bergek et al., 2008a); interaction between system components is often weak, actors cannot be expected to share a common goal, and the system components are not "directed or orchestrated by any specific actors" (Bergek et al., 2008a). (What is influencing the system without being under its control is called its environment (Hughes, 1983, p. 6).) The innovation system could be described as "constituted by elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge" Lundvall (1992, p. 3). Processes of learning are central to the concept (Lundvall, 1992; Johnson, 1992), interactive learning being enabled by "the networks of relationships which are necessary for any firm to innovate" (Freeman, 1995).

Innovation systems may be identified at the national, regional or sectoral level, or for a specific technology; the latter, frequently being labeled as 'technological innovation systems' (TIS), may focus on a technology in terms of products, knowledge, or both (Bergek et al., 2008a). Using a TIS approach could be "attractive when the focus of the enquiry is competition between various technologies to perform a certain function", for example to supply electricity (Jacobsson and Johnson, 2000). The TIS was described by Carlsson and Stankiewicz (1991) as "a network of agents interacting in a specific *economic/industrial area* under a particular *institutional infrastructure* or set of infrastructures and involved in the

generation, diffusion, and utilization of technology". A TIS may be regional, national or international, even though the nation-state often provides a natural boundary for the system (Carlsson and Stankiewicz, 1991). The TIS is generally considered to consist of the structural components actors, networks and institutions (i.e. the "rules of the game", such as laws, standards, cultural values etc.), and a set of system functions (e.g. Bergek et al., 2008a; Hekkert et al., 2007).

The rate and direction of technological change is, according to Hekkert et al. (2007), determined more by competition between innovation systems than between different technologies. Most fossil fuel energy technologies can be understood as part of larger technological systems, and these might be subject to various mechanisms of 'lock-in' (technological or institutional), obstructing a transition (Unruh, 2000). To tackle climate change, a fruitful approach could thus be to attempt to strengthen TISs of new, renewable energy technologies.

So far, little emphasis has been on using TIS for detailed analysis of deployment of new emerging energy technologies. As stated by Dewald and Truffer (2011): "Even though the TIS framework emphasizes the intrinsic socio-technical character of innovation processes, it has mostly focused on technology development and related supportive institutions. Market structures have received much less attention". Earlier TIS studies of PV, considering processes of deployment in parallel with processes of technology development and production, have been performed by Jacobsson and Bergek, 2004, Jacobsson et al., 2004 and Sandén et al., 2008. Dewald and Truffer (2011) however argue that "in order to properly address end-user-related dynamics into TIS analyses, the structural characterization of market formation processes has to be conceptualized much more explicitly".

3. What to focus on?

Studying a system, system boundaries should be defined; in order to communicate the results and compare them to other studies, it is of high importance that the precise unit of analysis is made explicit (Bergek et al., 2008a). Bergek et al. (2008a) outline three choices that need to be made when defining the TIS at focus: "(1) the choice between knowledge field or product as a focusing device, (2) the choice between breadth and depth, and (3) the choice of spatial domain". Sandén et al. (2008) suggest that system boundaries for a TIS should be defined for, at least, the four dimensions *technology*, *value chain*, *time* and *geography*. Boundaries for a TIS could also be defined empirically, by analyzing factors that promote or hinder the development of the system's functions (Johnson and Jacobsson, 2001); however, if the goal of the study is to derive policy recommendations, it is more reasonable to focus on setting the system boundaries as to delimit what is desirable/possible to govern, than to put effort into setting them as to delimit a "real" system.

Regarding the choice between breadth and depth, a focus on deployment implies that major parts of the PV value chain are excluded from the analysis; thus, such a study targets *on the depth* the end of the PV value chain. Also the precise definition of the *technology* at focus is a choice between breadth and depth, and is to be made regarding both how the technology has been produced and what it is used for (Sandén et al., 2008). Since the mechanisms behind market development (and thus technology deployment) may vary significantly between different market segments (Dewald and Truffer, 2011), it often makes sense not to consider *all* applications, but to identify and focus on those market segments that are of interest. In this paper, we focus on *grid-connected building-sited systems*, thereby excluding for example large scale solar parks and off-grid applications for summer houses, boats or parking meters. A narrower focus would also be possible, e.g. to focus only on BIPV technology. Regarding how the technology has been produced, the focus could be for example exclusively on thin film PV technology; however, with a focus on deployment it might be reasonable not to exclude any particular type of solar cells, but include all technologies that convert sunlight to electricity using the photovoltaic effect (and that are fit to use for the purpose of interest).

Even though countries that have reached high deployment have generally had successful PV industries as well (Dewald and Truffer, 2011), de la Tour et al. (2011) state that China's success in acquiring technologies for PV technology production without deploying much PV capacity in its territory "suggests that technology deployment and the diffusion of production technology are two distinct issues". What parts of the value chain that are at focus thus has implications on the choice of spatial domain. Upstream processes like silicon purification and wafer production are technologically very advanced; the markets for production equipment used in such processes are international, skilled workforce is recruited from around the world, and the produced goods are traded on an international market (de la Tour et al., 2011). Thus, such processes could be well understood as pertaining to a global TIS. However, it might also be fruitful to define a national TIS for these technologies, for example if the purpose of the analysis is to find out what policy a particular country should implement in order to strengthen its silicon/wafer industry. Also solar cells and modules are traded internationally (de la Tour et al., 2011). System installation, on the other hand, is an inherently much more local activity since the installation has to be performed on-site by the installing company. Further, electricity trading (which takes place at the very end of the PV value chain) is notoriously heavily regulated on the national, regional or local level (Gilbert and Kahn, 1996). A focus on deployment thus implies that a national (or regional) geographical system boundary would normally be suitable.

4. Applying the TIS framework on deployment of building-sited, grid-connected PV systems

In this section, we describe how we believe that the TIS framework could be used to analyze deployment of building-sited and grid-connected PV systems. The structural components of a TIS, as well as system functions that are common in the literature, are analyzed.

4.1. Structural components

In the literature, structural components of a TIS are normally grouped into the three categories 'actors', 'networks' and 'institutions' (e.g. Jacobsson and Bergek, 2004). Since few such structural components are in place when a radically new technology emerges, the TIS must "go through a formative phase, in which the constituent elements evolve and agglomerate through entry of firms and other organisations, formation of networks, institutional alignment and the accumulation of knowledge and physical artefacts" (Bergek et al., 2008b). Once the components are in place "the TIS is in a position to shift to a growth phase" and "a chain reaction of powerful positive feedbacks may materialize, setting in motion a process of cumulative causation" (Bergek et al., 2008b).

Also a TIS defined around deployment of PV could be said to go through a formative phase, in which new actors enter the system, networks are formed and institutions change or emerge. Structural components that are relevant for deployment of grid-connected building-sited PV are specified and discussed below.

Actors

Key actors for the deployment of PV systems might be architects, construction companies and roofers (for BIPV systems), city planners (to optimize the potential for PV electricity production of planned neighborhoods by orienting roofs and façades to the south and avoid shading), system installers/operating technicians¹, electricians, suppliers of PV system components (modules, inverters, etc.) and turn-key systems, banks (to give loans for investment in PV), interest organizations, government bodies, utilities, grid regulatory authorities, consultants, and traders of electricity.

¹ PV technology, however, requires very little maintenance.

Of particular importance to any TIS are the 'prime movers', which are "actors who are technically, financially and/or politically so powerful that they can initiate or strongly contribute to the development and diffusion of a new technology" (Jacobsson and Johnson, 2000). Actors that might become 'prime movers' in the case of PV deployment could include government bodies (e.g. by affecting institutions) or utilities (e.g. by engaging in solar electricity trade on a larger scale, by facilitating such trade, or by driving adaptation of the grid to the small-scale and intermittent character of PV). Individual firms could become prime movers if powerful enough, but prime movers of renewable technologies could also be "clusters of smaller firms organised in new networks", for example in the form of "suppliers of solar collectors form[ing] networks with construction firms as well as with larger housing co-operatives" (Jacobsson and Johnson, 2000), something that should hold for the PV case as well.

An important actor in the case of PV is the *system user*; apart from large scale solar parks, PV is a somewhat special technology for electricity production in that PV systems are often owned by private persons or small organizations, which are often also the owner of the building on which the system is sited². There might be a possibility that differences between wholesale and retail electricity prices could induce widespread investments in PV systems among these actors *before* it becomes attractive for utilities to invest in PV; in this case, one could think of these as jointly taking the role of a prime mover, without organizing themselves or having any (decisive) intention of driving technological change at a societal level. However, for high-tech technologies there is generally a significant "chasm" between a small number of early adopters and mainstream consumers, in the sense that mainstream consumers are significantly more hesitant to invest in new technology (Moore, 2001), which imposes a barrier to diffusion driven by private persons. Thus, incentives need to be large in order for mainstream consumers to be willing to invest. Even though end-user groups have been "proven to make substantial contributions to the development, dissemination and societal embedding of radical innovations", these have often been treated as exogenous in empirical TIS studies (Dewald and Truffer, 2011).

Another relevant group of actors is *electricity consumers*, which as a collective doubtlessly possess the economic power to strongly influence the demand for solar electricity on a deregulated electricity market. However, it is likely that they would need price incentives to do so (even though a small number of environmentally aware consumers might be willing to pay a proportionately high price for PV and other renewable electricity). Regulating authorities could, however, for example by imposing a major tax raise on fossil fuel generated electricity (thereby themselves taking the role of a prime mover) induce electricity consumers to drive diffusion of PV technology.

At large penetrations of PV electricity at the grid, utilities will have a crucial role in dealing with the intermittent character of PV electricity production, by providing regulating power, "smart grid" technology or energy storage; utilities could thus be an important prime mover at a stage where PV has already reached a certain diffusion. At an initial stage of PV diffusion, on the other hand, an important utility activity could be to facilitate connection to the grid for small scale electricity producers.

Networks

The essential function of networks is the exchange of information; networks become important when the needs for information are very diverse, making it risky and costly to try to satisfy them inhouse (Carlsson and Stankiewicz, 1991). Networks do not automatically form from the entry of organizations (Bergek et al., 2008b).

Networks may be market or non-market related (Jacobsson et al., 2004), formal or informal (Bergek et al., 2008a). The resource base of individual firms (and other actors) is increased by being strongly integrated into a network (Jacobsson et al., 2004).

² A variety of business models including third-party owners could, however, be implemented. The house owner would nevertheless have to be involved in some way.

Of particular importance are networks between actors, and an important role of policy is therefore to “help actors to find one another” (Jacobsson and Johnson, 2000). Important actor networks are *learning networks*, which “constitute important modes for the transfer, or sharing, of knowledge and also influence the perception of what is possible and desirable” linking “suppliers to users, related firms or competitors, or university to industry”. Of comparable importance are political networks, through which advocacy coalitions attempt to influence policy (Bergek et al., 2008b).

Networks are crucial for knowledge development and sharing related to PV deployment, and for feedback between system installers and owners. Examples of networks of importance would be business cooperation alliances (formed by architect firms, installers, etc.), city cooperation alliances (formed by city planners, architect firms etc.) and regional information centers which could organize seminars, study visits and conferences, etc., related to PV. Teamwork between architects and engineers can be important in an early design phase to decide what technical systems a building will have, since architects alone do not possess the advanced knowledge necessary (Kanters et al., 2012), which can be important for BIPV deployment.

Institutions

Institutions were defined by North (1990, p. 3) as “the rules of the game in a society or, more formally, [...] the humanly devised constraints that shape human interaction”. The institutional set-up strongly influences the “legitimacy of a new technology and its actors, their access to resources and the formation of markets”, and institutional change is therefore “at the heart of the process whereby new technologies gain ground” (Jacobsson and Bergek, 2004).

Some institutions might “influence connectivity in the system whereas others influence the incentive structure or the structure of demand” (Jacobsson and Bergek, 2004). North makes a distinction between formal (laws etc.) and informal (norms, cultural values) institutions, stating that “while formal rules may change overnight as the result of political or judicial decisions, informal constraints embodied in customs, traditions and codes of conduct are much more impervious to deliberate policies” (p. 6). In addition to laws, formal institutions also include government policy, standards, firm directives and contracts (Suurs, 2009). Informal institutions may be normative or cognitive, normative ones being “social norms and values with moral significance”, while cognitive ones “can be regarded as collective mind frames, or social paradigms” (Scott, 2001, in Suurs, 2009 (Suurs quoted, not Scott)). Normative rules might be for example “responsibility felt by a company to prevent or clean up waste”, while cognitive rules can be for example “search heuristics or problem-solving routines” (Suurs, 2009). While a TIS is in its formative stage, the institutional set-up (in particular regarding formal institutions) is usually badly aligned with the emerging technology, as institutions either are not in place or are maladapted. The alignment of institutions to the new technology is, however, a notoriously complicated process, and firms “compete not only in the market but also over the nature of the institutional set-up” (Bergek et al., 2008a).

Formal institutions relevant for deployment of PV technology may exist on a national, regional or local level, although the national government is often a natural upholder of such institutions; of particular importance might be taxation laws, net-metering policies, feed-in tariffs (FiT), tradable green certificates (TGC), investment subsidies, etc., stimulating the demand for PV technology, while for example subsidies for fossil fuels (or other renewable technologies) or rigid rules for building permits might be important institutions constraining PV deployment.

Systems of FiT and TGC are the most widely adopted frameworks to support PV and other renewable energy sources (Bergek and Jacobsson, 2010; Dusonchet and Telaretti, 2010). Under a FiT scheme, utilities are obliged to purchase renewable electricity produced within their service area at tariffs determined by public authorities and guaranteed for several years to come (Menanteau et al., 2003). For a technology like PV, where cost reductions of systems are rapid, it is important that the tariffs are reduced over time in order to prevent the

scheme from becoming too costly³ (which might happen if the incentives to invest in PV are too strong, thereby inducing unexpectedly widespread investments), which might impose a challenge for policy makers (Couture et al., 2010). Normally, the tariff remains constant for each producer under the guaranteed period, while new entrants are offered lower tariffs in later years (Fouquet and Johansson, 2008). FiT schemes can be funded through cross-subsidies among electricity consumers or through taxes (Menanteau et al., 2003), the most common solution being to pass the costs on to electricity consumers (Fouquet and Johansson, 2008). Bergek and Jacobsson (2010), reviewing several assessments of FiTs in various countries, conclude that the main advantage FiT schemes is their “effectiveness in promoting technology development and diffusion”. Kåberger et al. (2004) state that differentiated long-term FiTs contracts “could match the significantly different needs of ... different technologies and could be developed to drive development by reducing the prices for every new generation of electricity plants built” and Dusonchet and Telaretti (2010) state that FiT policies have been successful for reaching high levels of deployment in several countries.

A TGC framework is based on trade of certificates that are initially awarded to producers/distributors of renewable electricity. The TGCs can then be sold at a free market, demand being created by obligations⁴ on other electricity producers/distributors to possess certificates corresponding to a certain share of their produced or distributed electricity. According to Bergek and Jacobsson (2010), “a TGC framework should be selected if the overriding concern is to minimize short term social costs of reaching a certain goal with a high degree of predictability” and “cannot be expected to also drive technical change, keep consumer costs down and be equitable” (Bergek and Jacobsson, 2010).

Net metering is a policy to allow small scale electricity producers to, as far as invoicing concerns, deduct electricity that they feed into the grid from what they take out, thus being charged for their *net* consumption over a certain period. If invoicing is made every month, the system could be designed so that any surplus in the summer months could be “saved” to cover for winter usage. Net metering has the benefit of not requiring any subsidies, although its power to create incentives is limited to providing the possibility of “saving” electricity for later use.

Standards is a type of formal institutions that are usually international. An important function of technology standards is to promote diffusion of a technology (Ma, 2010). Standards may decrease the uncertainty for investors, by guaranteeing the compatibility, safety and durability of products. European standards regarding safety and durability exist for modules, inverters, etc. For BIPV systems, the lack of standardized size of PV modules has imposed a problem (van Noord, 2010). Standards could also be important to guarantee the quality of PV system installers.

On the EU level, rules regarding energy efficiency of buildings could be an important driver of PV diffusion. In 2010, a directive was adopted mandating that all new buildings within EU must be “Nearly Zero Energy Buildings” after 2019, buildings for which PV is an “almost unavoidable tool” (Musall et al., 2010).

Informal institutions affecting the rate of deployment could be related to how the PV technology, or renewable energy technologies at large, are perceived in society; a high legitimacy is an important factor for the market to be able to grow (Jacobsson and Bergek, 2004). Willingness to pay a higher price for solar electricity in order to “do something good” might be an important normative informal institution to spur market growth. A belief that PV is economically and/or technologically superior to, for example, small scale wind power might be an example of a relevant cognitive informal institution.

The need to take all relevant institutions into consideration is demonstrated by difficulties to reach high levels of PV deployment in countries like France and Greece, where

³ An alternative could be to put some kind of cap on the FiT scheme.

⁴ A TGC framework could also be based on voluntary demand for certificates, although it “can be considered as a regulatory instrument for long-term wider use of [renewable energy] only if demand is set and mandatory” (Oikonomou and Mundaca, 2008).

diffusion has been hampered by regulative and administrative barriers notwithstanding favorable FiT schemes (Dusonchet and Telaretti, 2010). Experiences from Spain, where a policy similar to the German FiT scheme was implemented, show that “the transfer of a seemingly successful support scheme can quickly run into problems if the institutional context in which the scheme was developed is overlooked” and that “the effectiveness may be seriously hampered if the associated support by local market processes is not available” (Dewald and Truffer, 2011).

4.2. Functions

A framework for analyzing the development and diffusion of emerging technologies must be dynamic. To focus merely on the structure of an innovation system is insufficient when analyzing the dynamics of cumulative causation; instead, one needs to focus on a number of key processes, in the literature generally referred to as ‘functions’ (e.g. Bergek et al., 2008a; Hekkert et al., 2007; Suurs and Hekkert, 2009). Hekkert et al. (2007) state that while an analysis considering system structures alone would provide insights into, for example, how “German sustainable energy producers receive higher prices and are able to negotiate longer-term contracts” than their Dutch colleagues, a dynamic system analysis could add knowledge about how the regulations that benefit these producers came in place through the work of renewable energy lobby, opposition, and external events. Bergek et al. (2008a), pointing to the difficulties in evaluating the “goodness” or “badness” of the structural composition of the system “without referring to its effects on the innovation process”, rhetorically ask: “how do we know whether the existence of a particular actor network is a strength (e.g. a source of synergy) or a weakness (e.g. a source of lock-in or “group-think”) ... without identifying its influence on the innovation process and its key sub-processes?”. Functions “constitute an intermediate level” between the structural components and the performance of the TIS (Jacobsson et al., 2004), and can be described as “emergent properties of the interplay between actors and institutions” which “can be assessed in order to derive policy recommendations, e.g. for supporting the development of a specific technology” (Markard and Truffer, 2008).

Since *all* activities cannot possibly be mapped, only relevant activities – i.e. those that influence the goal of the innovation system, which is to “develop, apply, and diffuse new technological knowledge” – should be mapped (Hekkert et al., 2007). The exact number of functions is of course somewhat arbitrary, and various sets have been presented, something that, as stated by Suurs (2009) “raises the question whether a set of system functions actually covers relevant processes and whether it is complete”. Suurs however answers this questing by stating that “[a] comparison of various lists shows that differences are mostly superficial and reside in the way that various activities are clustered” and that “lists of system functions need to be confirmed (or rejected) by empirical evidence”. Indeed, studies have shown that common functions in the literature correspond “well to the empirical data relevant in the field of sustainability innovations” (Suurs and Hekkert, 2009).

Below, we elaborate on the set of seven functions presented by Bergek et al. (2008a), to see how these could be used to analyze deployment of grid-connected building-sited PV.

Market formation

The formation of markets is intimately linked to deployment of new technology. It is not only a prerequisite for deployment, but rather an aspect of it. In a sense, it *is* deployment, since actual market development can be expressed in terms of installed capacity over time (Bergek et al., 2008a). What is *driving* market formation is more difficult to analyze, and requires in-depth knowledge about the TIS (Bergek et al., 2008a).

Normally, an emerging TIS first goes through a phase of “nursing markets”, i.e. small niche markets that give the new technology a protected space, and subsequently one of “bridging markets”, where volumes increase and the TIS grows in terms of number of actors, before mass markets (in terms of volume) may evolve (Bergek et al., 2008a). Since new

innovations are often crude and inefficient, and cannot easily compete with incumbent technologies, they might need protected space (Kemp et al, 1998). Nursing markets are important for learning processes and knowledge development, which lead to increased price/performance relations, and because they provide incentives for firm entry along the whole value chain (Marinova and Balaguer, 2009). Protected space can thus be created through temporary niche markets for specific applications of the technology, which can give actors an opportunity to learn about the technology, and for expectations to develop (stimulating the functions 'knowledge development and diffusion' and 'influence on the direction of search') (Hekkert et al., 2007). The first significant commercial market for the PV technology was the satellite industry around the 1960s, and since then other off-grid applications where the high costs have been of less importance, such as parking meters, watches, summer homes, remote villages, have provided additional niche markets (Jacobsson et al., 2004) in a process which could be described as "a cumulation of niches"⁵ (Geels, 2002).

Dewald and Truffer (2011), stating that the "three-step model" described above, being akin to theories of technology diffusion using S-shaped curves to describe increased market shares over time (see Rogers, 2003), albeit working "particularly well for those innovations that consist of completed products being adopted by a clearly delimited population of users" is not apt for analyzing "radical innovations and early niche market developments where product design, use patterns, price-performance ratios are still in flux"; as an example of the latter kind of technology, the authors bring up PV. The authors argue that in order to understand why policy succeeds in some cases and fails in others, it is necessary to reach deep insights into the market formation process. Elaborating on "how a more explicit treatment of market processes can be conceptualized within the TIS framework", Dewald and Truffer promote a focus on "market segments and their interactions (instead of aggregate indicators for general market growth)", market segments being "sub-system structures that serve specific user segments and that are characterized by specific product forms and related actors, networks and institutions", and which are each "likely to generate specific support for the overall functionality of the TIS"; thus, Dewald and Truffer conclude, "a broad portfolio of market segments stabilizes the entire TIS, because each segment broadens the basis on which developments can draw. Market subsidy schemes should therefore leave room for variety in designs and market contexts". For the German PV TIS, Dewald and Truffer identified four market segments for on-grid⁶ PV applications: *centralized PV power systems*, *small-scale homeowner systems*, *large-scale roof-mounted systems* and *civic corporate solar systems*. Grid-connected building-sited PV could thus be divided into smaller market segments – which ones these are may depend on the specific case, e.g. which country is studied. For example, BIPV technology could be considered a market segment – or a group of market segments.

Market segments could support or obstruct the development of other market segments; for example, "if operability of the technology could already be proved for a specific application domain, barriers for other market segments may be reduced" (an investment in a cooperatively owned system, for example, "often serves as a market entry to homeowners who ultimately set up a PV system on their own property"), but market segments could also "compete for resources, for access to pre-products and consumers and drive up prices" (Dewald and Truffer, 2011).

Bergek et al. (2008a), drawing upon Hughes (1983), state that "[i]nstitutional change, e.g. the formation of standards, is often a prerequisite for markets to evolve" for an emerging TIS. This is particularly true for a technology like PV, for which issues like safety, durability and compatibility (with the electricity grid, between different system components, and, for

⁵ Such trajectories of *niche-cumulation* constitute a general pattern through which radical innovations gain ground and eventually become widely adopted (Geels, 2002).

⁶ Accounting for less than 1 % of installed German capacity, off-grid applications (which could otherwise have been treated as one or more market segments) were excluded from the study performed by Dewald and Truffer.

BIPV systems, with other building elements) are crucial. Also institutions increasing demand by creating economic incentives, such as taxation laws, feed-in tariffs or subsidies, are crucial for market development in a situation where the PV technology has not yet achieved grid parity. Such financial supports should be regarded as temporary, to be phased out as the PV technology gain competitiveness. It is of high importance, however, that policy is *transparent, comprehensible and long-term* in order for investors and industry to feel reasonably secure about what kind of game they will play over the coming years if they are to invest in PV systems, sign (possibly long-term) contracts with suppliers, hire and educate new staff, etc.

Architects could contribute to new markets being opened up by developing new kinds of buildings. They could also “stimulate house-owners to invest by including PV power systems into construction plans” (Dewald and Truffer, 2011).

In order to understand “the sequence of the *formation* of markets” this function needs to be analyzed both in terms of the actual market development, and what was driving this development (Bergek et al., 2008a). While the actual market development can relatively easily be measured (for example in terms of installed capacity for a renewable electricity technology), its driving forces might be more difficult to analyze (Bergek et al., 2008a). An analysis should “assess what phase the market is in (nursing, bridging, mature), who the users are and what their purchasing processes look like, whether the demand profile has been clearly articulated and by whom, if there are institutional stimuli for market formation or if institutional change is needed” (Bergek et al., 2008a). The stage of development and mutual interdependence of different market segments could be assessed (Dewald and Truffer, 2011).

Knowledge development and diffusion

This function encompasses different learning processes. Indeed, the activity of learning is central in the innovation systems approach, and, assuming that knowledge is “the most fundamental resource in the modern economy”, learning would, accordingly, be the most important process (Lundvall, 1992). In order to bring an innovation to the market, informal, experience-based learning processes are of particular importance; these might be referred to as Doing, Using and Interacting (DUI) processes of learning⁷ (Lundvall, 2007; Jensen et al., 2007). DUI processes relate intimately to the knowledge types⁸ ‘know-how’ and ‘know-who’, which are often tacit and “rooted in practical experience” (Jensen et al., 2007). The non-rival nature of knowledge allows for *knowledge spillover* “whereby investments in knowledge creation by one party produce external benefits by facilitating innovation by other parties” (Jaffe et al., 2000). For the transfer of knowledge, networks are crucial. Education and training related to implementation could be important for all relevant actors involved in PV deployment.

Bergek et al. (2008a) bring up the example of PV in Germany (summarizing the results of Jacobsson et al., 2004) as an example of how knowledge may develop in an emerging TIS over time:

“Initially, the type of knowledge development was limited to the scientific/technological field and the source was R&D on various competing designs for solar cells. The knowledge base was subsequently broadened as the system expanded along the entire value chain. First, application-specific knowledge was developed down-stream as firms experimented with solar cells as a building element. Part of the knowledge development took place in schools of architecture where “solar architects” developed new design concepts. Second, upstream technological knowledge was enhanced

⁷ In contrast to DIU learning stand Science, Technology and Innovation (STI) processes of learning, which are more related to codified knowledge and science (Lundvall, 2007; Jensen et al., 2007).

⁸ The other two knowledge types mentioned by the authors – know-what and know-why – are more related to “reading books, attending lectures and accessing data bases” (Jensen et al., 2007).

through R&D performed by the capital goods industry. A significant aspect of that knowledge development was, however, also a very practical and problematic learning process to build automated production lines for the manufacturing of solar cells.”

Jacobsson et al. (2004) found that in industry-academia links ‘downstream’ relationships involving architects were of particular importance for this TIS, and some architects received professorships in solar architecture “as a result and indication of a learning process”, something that enlarged and supplied resources to the TIS (Jacobsson et al., 2004). Researchers in solar architecture could be important in designing new BIPV solutions.

The development and diffusion of new business models for PV ownership could be a crucial activity pertaining to this function.

It is also important that knowledge is strengthened regarding the planning phase of PV projects – here, a variety of software tools of varying complexity are available for the different stages of the planning process, which can be used for example to model electricity production based on geography, architecture and PV technology, etc. A literature review and a survey performed by Horvat et al. (2011) “strongly indicate the need for further development of software tools for solar architecture, focusing upon tools appropriate for architects: a visual tool that is easily interoperable between different modeling software packages, and which generates clear and meaningful results that are compatible with architectural design workflow”. For small projects, or at an early stage of planning for larger projects, simple modeling programs that are free of charge may be important to spread information about electricity production potential. GIS technology can be used to gain knowledge about PV electricity production potential in larger areas (e.g. for an urban area or for a whole country) (Šúri et al., 2005; Charabi and Gastli, 2011; Choi et al., 2011).

Influence on the direction of search

This function captures incentives and/or pressures for firms and other organizations to enter the TIS, as well as mechanisms influencing the direction of search *within* the TIS “in terms of different competing technologies, applications, markets, business models, etc.” (Bergek et al., 2008a). It “refers to those activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users”, an example being long-term goals set by governments to reach a certain share of renewable energy (Hekkert et al., 2007). Apart from the influence of market and government, the function also reflects “interactive and cumulative process[es] of exchanging ideas between technology producers, technology users, and many other actors, in which the technology itself is not a constant but a variable” (Hekkert et al., 2007). Changes in the surrounding “socio-technical landscape” (Geels, 2011), e.g. through climate change debates or surging oil-prices, may influence the direction of search. Growth in TISs in other countries could have an influence on the direction of search (Bergek et al., 2008a).

The strength of this function can be indicated by beliefs in the potential for growth, price incentives (including taxes), regulatory pressures, and “the articulation of interest by leading customers” (Bergek et al., 2008a). Also “the number of articles in professional journals that raise expectations about new technological developments” can be an indication (Hekkert et al., 2007); this might influence expectations regarding deployment, since technological development could open up for new applications.

Entrepreneurial experimentation

As stated by Hekkert et al. (2007), “[t]he presence of active entrepreneurs is a first and prime indication of the performance of an innovation system. When entrepreneurial activity lags behind, causes may be found in the other ... functions”. Risky experiments of entrepreneurs are important to cope with the large uncertainties that are present in an emerging TIS (Hekkert et al., 2007; Bergek et al., 2008a).

Entrepreneurial activities may, in turn, strengthen other function, giving rise to virtuous circles (Hekkert et al., 2007); firm entry/activity may lead to the creation of new knowledge, supply of resources, development of new designs within a certain technology field, and may stimulate market formation (Jacobsson and Bergek, 2004). Bergek et al. (2008a) mention two reasons why the entry of firms into an emerging TIS is important for the development of positive externalities; with support in Lieberman and Montgomery (1988), they state that “new entrants may resolve at least some of the initial uncertainties with respect to technologies and markets” which would strengthen the functions ‘influence on the direction of search’ and ‘market formation’, and, referring to Carroll (1997), they state that firms may, by their very entry into an emerging TIS, contribute to its legitimation.

The development and implementation of new business models can be of high importance for increased deployment of PV. Here, entrepreneurial experimentation may play an important role. For example, third-party ownership could be an effective solution to cope with high upfront costs and perceived hassle among end users (Yang, 2010).

Entrepreneurs performing demonstration projects, showing different kinds of deployments, could influence the direction of search. We expect demonstration projects to be particularly important for BIPV, for which very little experience exists worldwide.

The entry of firms into various points in the value chain is central to the process by which a new TIS emerges and grows; new firms entering the TIS bring new knowledge and resources, and contribute to division of labor by specializing themselves (Jacobsson et al., 2004; Jacobsson and Bergek, 2004).

To analyze this function, an analyst could map the number of new entrants (including diversifying incumbent firms), the “number of different types of applications”, and “the breadth of technologies used and the character of the complementary technologies employed” (Bergek et al., 2008a).

Legitimation

This function captures matters related to “social acceptance and compliance with relevant institutions” (Bergek et al., 2008a). It has (together with ‘development of positive externalities’) suffered an undeserved lack of attention in the technology management and policy literature (Bergek et al., 2008b). Relevant actors’ perception of the new technology (and its proponents) as “appropriate and desirable” might lead to resources being mobilized, formation of demand, and political strength being gained by actors in the new TIS (Bergek et al., 2008a). By influencing expectations among managers (and thus their strategy), legitimation might influence the direction of search (Bergek et al., 2008a). We expect this function to be very important for the deployment of PV; lack of legitimacy can guide the search away from renewable energy technologies, and block the supply of resources and the formation of markets (Jacobsson and Bergek, 2004).

Cooperatively owned PV systems can lead to increased legitimacy by reaching new end-user groups (Dewald and Truffer, 2011).

Advocacy coalitions may create legitimacy for the new technological trajectory through exercising ‘influence on the direction of search’ by putting a new technology on the agenda, and through contributing to ‘resource mobilization’ and ‘market formation’ by performing lobbying (Hekkert et al., 2007). Legitimation through lobbying performed by activists and interest organizations was decisive for the deployment supporting schemes for PV in Germany (Bergek et al., 2008a; Jacobsson and Lauber, 2006).

To map this function, the “rise and growth of interest groups and their lobby actions” can be analyzed (Hekkert et al., 2007), as well as “the legitimacy of the TIS in the eyes of various relevant actors and stakeholders” (Bergek et al., 2008a). It is necessary to understand the strength of legitimacy in terms of compliance with legislation and value base, how demand, legislation and firm behavior is influenced by legitimacy, and what is influencing legitimacy (Bergek et al., 2008a).

Resource mobilization

Resources in the form of financial as well as human capital are necessary for all activities in the TIS, for example the production of knowledge (Hekkert et al., 2007). This function “reflects the participation of educational and financial organizations, such as universities and venture capital firms” (Sandén et al., 2008). Examples of activities being embraced by this function are funds made available for R&D programs and niche experiments (Hekkert et al., 2007) (this is, however, probably more relevant for technology development than for deployment). Also increased possibilities to get loans for investing in PV systems for different types of potential investors may be an important aspect of this function, or better conditions for such loans. Mobilized financial resources for demo projects might be important.

Even though Hekkert et al. (2007) state that this function is “difficult to map by means of specific indicators over time”, Bergek et al. (2008a) suggest that resource mobilization could be measured analyzing “rising volume of capital”, “increasing volume of seed and venture capital”, “changing volume and quality of human resources (e.g. number of university degrees)”, and “changes in complementary assets”. Hekkert et al. (2007) suggest that “the best suited method to create insight in the fulfillment of this function is to detect, by means of interviews, whether or not inner core actors perceive access to sufficient resources as problematic” (Hekkert et al., 2007).

Development of positive externalities

The development of positive externalities is to a high extent dependent on the entry of new firms, which may resolve some of the initial uncertainties in an emerging TIS (which would strengthen ‘influence on the direction of search’ and ‘market formation’), contribute to legitimation (by their very entry or by strengthening the political power of advocacy coalitions), and enrich the amount and variety of actors within the TIS which might increase the chances of new combinations to arise (Bergek et al., 2008a). Thus, “new entrants may contribute to a process whereby the functional dynamics of the TIS are strengthened, benefiting other members of the TIS through the generation of positive externalities. This function is thus not independent but works through strengthening the other six functions. It may, therefore, be seen as an indicator of the overall dynamics of the system” (Bergek et al., 2008a). Such dynamics might be strengthened by co-location of firms, since some economies are external to firm but internal to location; for example, as a *pooled labor market* emerges, knowledge may be transferred to a firm by recruiting staff from earlier entrants, and as firms *specialize in providing intermediate goods and services* costs are reduced and further ‘knowledge development and diffusion’ may occur (Bergek et al., 2008a).

5. Concluding remarks

Our analysis shows how the TIS framework captures components and processes that are relevant for PV deployment. Even though a focus on deployment means that major parts of the PV value chain are excluded from the analysis, the system is still complex with a variety of actors bringing different kinds of competences.

All three groups of structural components are doubtlessly crucial for PV deployment. It is therefore important to map relevant actors, networks and institutions, assess these, and map what is required in terms of for example competences among actors and institutional alignment.

The importance of the functions brought up in this paper, however, might vary between different functions; for example, while ‘market formation’ and ‘knowledge development and diffusion’ are absolute necessities for deployment, ‘resource mobilization’, might be more crucial for enabling technology development, which is more capital intensive and requires more advanced knowledge than deployment. The difficulties in studying the functions might also vary between functions. Some of them can be relatively easily analyzed through quantitative measures, while others require qualitative analysis. ‘Knowledge development

and diffusion', for example, might be more difficult to measure for deployment than for technology development, where number of patents, learning curves etc. could be used in a straightforward way.

The framework could be used to derive policy recommendations, or for comparable studies between countries.

References:

- Bergek, Anna and Staffan Jacobsson, 2010: Are tradable green certificates a cost-efficient policy driving technical change or a rent-generating machine? Lessons from Sweden 2003-2008. *ENERGY POLICY*, (38), 3, 1255-1271.
- Bergek, Anna, Jacobsson, Staffan, Carlsson, Bo, Lindmark, Sven and Rickne, Annika (2008a): Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy* 37 (2008) 407–429.
- Bergek, Anna, Jacobsson, Staffan and Sandén, Björn (2008b): 'Legitimation' and 'development of positive externalities': Two key processes in the formation phase of technological innovation systems, 2008, *Technology Analysis & Strategic Management*, (20), 5, 575-592.
- Carlsson, B. and Stankiewicz, R. (1991): On the Nature, Function, and Composition of Technological systems. *Journal of Evolutionary Economics* 1 (1991) 93-118.
- Carroll, G. (1997): Long-term evolutionary changes in organizational populations: theory, models and empirical findings in industrial demography. *Industrial and Corporate Change* 6, 119–143.
- Charabi, Yassine and Gastli, Adel, 2011: PV site suitability analysis using GIS-based spatial fuzzy multi-criteria evaluation. *Renewable Energy*, ISSN 0960-1481, 2011, Volume 36, Issue 9, pp. 2554-2561.
- Choi, Yosoon, Jeffrey Rayl, Charith Tammineedi and Jeffrey R.S. Brownson, 2011: PV Analyst: Coupling ArcGIS with TRNSYS to assess distributed photovoltaic potential in urban areas. *Solar Energy*, Volume 85, Issue 11, November 2011, Pages 2924-2939.
- Couture, Toby D., Karlynn Cory, Claire Kreycik and Emily Williams, 2010: A Policymaker's Guide to Feed-in Tariff Policy Design. National Renewable Energy Laboratory, Technical Report NREL/TP-6A2-44849, July 2010.
- de la Tour, A, Glachant, M and Ménière, Y, 2011: *Innovation and international technology transfer: The case of the Chinese photovoltaic industry*. *Energy Policy* Volume 39, Issue 2, February 2011, Pages 761-770.
- Dewald, U. and B. Truffer, 2011. Market Formation in Technological Innovation Systems—Diffusion of Photovoltaic Applications in Germany. *Industry and Innovation*, Vol. 18, No. 3, 285–300, April 2011.
- Dusonchet, Luigi and Enrico Telaretti, 2010: Economic analysis of different supporting policies for the production of electrical energy by solar photovoltaics in western European Union countries. *Energy Policy* 38 (2010) 3297–3308.
- EurObserv'ER (2012): Photovoltaic barometer. *Le journal du photovoltaïque*, N° 7 – 2012.
- Fouquet, D. and Johansson, T.B. (2008). "European Renewable Energy Policy at Crossroads: Focus on Electricity Support Mechanisms." *Energy Policy*, (36, 11); pp. 4079– 4092.
- Freeman, C. (1995): The 'National System of Innovation' in historical perspective. *Cambridge Journal of Economics* 19 (1995) 5-24.
- Geels, F. W., 2011: *The multi-level perspective on sustainability transitions: Responses to seven criticisms*. *Environmental Innovation and Societal Transitions* 1 (2011) 24–40.
- Geels, F. W., 2002. *Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study*. *Research Policy*, Volume 31, Issues 8–9, December 2002, Pages 1257–1274.
- Gilbert, Richard J. and Edward P. Kahn (1996). *International Comparisons of Electricity Regulation*. Cambridge University Press, Cambridge, UK.

- Hekkert, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S., and Smits, R. E. H. M. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, 74(4), 413-432.
- Horvat, Miljana, Marie-Claude Dubois, Mark Snow, Maria Wall, 2011: *International survey about digital tools used by architects for solar design*. Solar heating and cooling programme, International Energy Agency.
- Hughes, T., 1983. *Networks of Power*. Johns Hopkins University Press, Baltimore.
- IEA, 2012. *Energy Technology Perspectives 2012 – Pathways to a Clean Energy System*. International Energy Agency, France.
- Jacobsson, Staffan and Bergek, Anna (2004): Transforming the energy sector: the evolution of technological systems in renewable energy technology. *Industrial and Corporate Change*, Vol. 13(5): 815–849.
- Jacobsson, S., Lauber, V., 2006. The politics and policy of energy system transformation – explaining the German diffusion of renewable energy technology. *Energy Policy* 34, 256-276.
- Jacobsson, Staffan, Sandén, Björn A. and Bångens, Lennart (2004): Transforming the Energy System – the Evolution of the German Technological System for Solar Cells. *Technology Analysis & Strategic Management*, Vol. 16, No. 1, 3–30, March 2004.
- Jacobsson, S. and Johnson, A. (2000): The Diffusion of Renewable Energy Technology: An Analytical Framework and Key Issues for Research, *Energy Policy* 28 (2000) 625-640.
- JAFFE, ADAM B., MANUEL TRAJTENBERG, AND MICHAEL S. FOGARTY (2000): The American Economic Review, Vol. 90, No. 2, Papers and Proceedings of the One Hundred Twelfth Annual Meeting of the American Economic Association (May, 2000), pp. 215-218.
- Jensen, Morten Berg, Björn Johnson, Edward Lorenz, Bengt Åke Lundvall, 2007: Forms of knowledge and modes of innovation. *Research Policy* 36 (2007) 680–693.
- Johnson, Anna and Jacobsson, Staffan, 2001. Inducement and blocking mechanisms in the development of a new industry: the case of renewable energy technology in Sweden. In R. Coombs, K. Green, A. Richards and V. Walsh (eds), *Technology and the Market. Demand, Users and Innovation*, pp. 89-111. Edward Elgar: Cheltenham.
- Johnson, Björn, 1992: Institutional Learning. In Lundvall, Bengt-Åke (ed.) (1992).
- Kanters, Jouri, Marie-Claude Dubois and Maria Wall, 2012: Architects' design process in solar-integrated architecture in Sweden. *Architectural Science Review*, iFirst, 2012, 1–11.
- Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. *Technology Analysis and Strategic Management* 10, 175–195.
- Kåberger, Tomas, Sterner, Thomas, Zamanian, Max, Jürgensen, Anna, 2004. Economic efficiency of compulsory green electricity quotas in Sweden. *Energy and Environment* 15 (4).
- Lieberman, M. and Montgomery, C. (1988): First-mover advantages. *Strategic Management Journal* 9, 41–58.
- Lundvall, Bengt-Åke (2007): *Innovation System Research – Where it came from and where it might go*. GLOBELICS Working Paper Series, No. 2007-01.
- Lundvall, Bengt-Åke (ed.) (1992): *National Systems of Innovation: Towards a Theory of Innovation and Interactive Learning*. Pinter, London.
- Ma, Zhongfa, 2010: On Relationships between Technology Standards and Patented Technology Licensing. *Journal of Politics and Law*, vol. 3 no. 1, March 2010.
- Marinova, Dora and Antonio Balaguer, 2009: Transformation in the photovoltaics industry in Australia, Germany and Japan: Comparison of actors, knowledge, institutions and markets. *Renewable Energy*, Volume 34, Issue 2, February 2009, Pages 461–464.
- Markard, J. and Truffer, B., 2008. Technological Innovation Systems and the Multi-Level Perspective: Towards an Integrated Framework. *Research Policy* 37(4): 596-615.
- Marshall, A. (1920): *Principles of Economics*, 8th ed. Macmillan and Company Ltd., London.

- Menanteau, P., Finon, D. and Lamy, M.-L. (2003): Prices versus quantities: choosing policies for promoting the development of renewable energy, *Energy Policy*, 31 (8): 799-812.
- Moore, G.A., 2001. *Crossing the Chasm: Marketing and Selling High-tech Products to Mainstream Customers*. HarperCollins Publishers, New York, NY
- Musall, Eike, Tobias Weiss, Karsten Voss, Aurélie Lenoir, Michael Donn, Shaan Cory and François Garde, 2010: *Net Zero Energy Solar Buildings: An Overview and Analysis on Worldwide Building Projects*. Presented at EuroSun 2010, International Conference on Solar Heating, Cooling and Buildings, Graz, Austria.
- Myrdal, G. (1957): *Economic Theory and Underdeveloped Regions* (London, Ducksworth Pubs., 1957).
- Nelson, Richard R. and Nelson, Katherine (2002): Technology, institutions, and innovation systems. *Research Policy* 31 (2002) 265-272.
- North, D. C. (1990): *Institutions, Institutional Change and Economic Performance*. Cambridge University Press, New York.
- Oikonomou, Vlasis and Luis Mundaca, 2008. Tradable white certificate schemes: what can we learn from tradable green certificate schemes? *Energy Efficiency* (2008) 1:211-232.
- Rogers, E. M. (2003) *Diffusion of Innovations*, 5th edn (1st edn 1962). New York: Free Press.
- Sandén, B. A., Jacobsson S., Palmblad, L. and Porsö, J. (2008). Assessment of the impact of a market formation programme on the Swedish PV innovation system. Presented at the DIME International Conference "Innovation, sustainability and policy" 11-13 September 2008.
- Scott, W. R. (2001): *Institutions and Organizations*. Sage Publications, London.
- Šúri, Marcel; Huld, Thomas A; Dunlop, Ewan D (2005): PV-GIS: a web-based solar radiation database for the calculation of PV potential in Europe. *International Journal of Sustainable Energy*, ISSN 1478-6451, 06/2005, Volume 24, Issue 2, pp. 55-67.
- Suurs, Roald A.A. (2009): *Motors of Sustainable Innovation – Towards a theory on the dynamics of technological innovation systems*. (Thesis).
- Suurs, Roald A.A. and Hekkert, Marko P. (2009): Cumulative causation in the formation of a technological innovation system: The case of biofuels in the Netherlands. *Technological Forecasting & Social Change* 76 (2009) 1003-1020.
- Unruh, Gregory C. (2000): Understanding carbon lock-in. *Energy Policy* 28 (2000) 817-830.
- van Noord, Michiel, 2010: *Byggnadsintegrerade solcellsanläggningar – Europeisk Best-Practice*. Elforsk rapport 10:41.
- Yang, Chi-Jen, 2010: Reconsidering solar grid parity. *Energy Policy* 38 (2010) 3270–3273.