MASTER'S THESIS 2008:14

Increasing the rate of solar cell diffusion in Japan

Dynamics of the PV innovation system, 1973–2007

KRISTIAN JELSE & HANNES JOHNSON

Division of Environmental Systems Analysis
Department of Energy and Environment
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2008

Increasing the rate of solar cell diffusion in Japan –
Dynamics of the PV innovation system, 1973–2007
KRISTIAN JELSE & HANNES JOHNSON

ESA Report No. 2008:14
ISSN: 1404–8167

Division of Environmental Systems Analysis
Department of Energy and Environment
Chalmers University of Technology
SE-412 96 Göteborg
Sweden

Telephone: +46 (0)31-772 1000

Chalmers Reproservice, Göteborg, 2008

Abstract

Today, energy supply is the sector that accounts for the largest share of anthropogenic greenhouse gas emissions on a global scale. One of the actions that could contribute to a future stabilisation of the concentration of greenhouse gases in the atmosphere is thus structural change of the energy system towards a higher share of renewable energy. In order to overcome institutional barriers, develop the technology and create an initial market for renewables, public policies are needed.

To design efficient policy instruments, one needs knowledge about what challenges face the growth of the new technology. One analytical framework that tries to capture and describe the most important inducement and blocking mechanisms in such a growth process is the technological innovation systems (TIS) approach. To understand, not only the structure of the system, but what goes on inside it, one can analyse what key processes influence the development, diffusion and use of the technology – the functional dynamics of the technological innovation system.

This study is carried out as a master's thesis at Chalmers University of Technology, and included a stay for three months as visiting researchers at the University of Tokyo. It uses the functional dynamics approach to analyse the Japanese solar cell (PV) innovation system in a historical perspective. The goal is to understand the diffusion of PV in Japan, and more specifically to identify the blocking mechanisms facing the innovation system today, hindering further diffusion of the technology. Key policy issues, related to the blocking mechanisms, will also be pointed out. To assess how well the system is performing, the German PV innovation system is used as a comparison and contrast.

The analysis shows that the main differences between how PV has developed in Japan and Germany, is due to the difference in how nuclear power has developed and the effects of the involvement of environmental organisations, such as non-governmental organisations (NGOs) and political coalitions.

Seven blocking mechanisms for diffusion of PV in Japan, ranging from the lack of clear targets and someone responsible for them to the fact that nuclear power often is seen as a contrast to renewables, were identified. Based on these, five policy issues were suggested, including official targets for PV diffusion and a long-term financial incentive for PV users.

Acknowledgements

This study was carried out as a master's thesis at the division of Environmental Systems Analysis at Chalmers University of Technology, and would not have been possible without the kind help of many people. First, we would like to thank our supervisor Associate professor Björn Sandén for helping us make this study become a reality from initial idea to final report. The suggestions from Lennart Stenberg on the scope, and the discussions with Professor Staffan Jacobsson about the development of PV in Germany, were also highly appreciated.

In Japan, we would like to thank everyone at the Iwata/Yarime laboratory, where we were kindly hosted for three months. We are especially grateful to Associate professor Masaru Yarime for his help with practicalities, contacts and valuable insights. We would also like to thank Dr. Katsumi Kushiya for his help with contacting people in the Japanese PV industry, and for sharing some of his knowledge of PV. We are also grateful to Elin Vinger, Izumi Tanaka and Marie-Louise Karlsson at the Swedish Embassy Science & Technology Office for allowing us to accompany them to some initial interviews, and to Marjan Prent at the Netherlands Embassy for valuable discussions.

Finally, we would like to thank all the people that kindly agreed to meet with us and share their knowledge and views of PV in Japan (see Appendix A). Without them, this study would not have been possible.

Financial support came from scholarships from Stipendiestiftelsen för studier av japanskt samhällsliv, Stiftelsen Marcus och Amalia Wallenbergs minnesfond (via Sweden-Japan Foundation), Ångpanneföreningens forskningsstiftelse and Sveriges Ingenjörers Miljöfond.

Contents

1 Introduction

Today, energy supply is the sector that accounts for the largest share of anthropogenic greenhouse gas emissions on a global scale (IPCC, 2007). One action that could contribute to a future stabilisation the concentration of greenhouse gases in the atmosphere is a structural change of the energy system towards a higher share of renewable energy, replacing fossil fuel-based power plants. There are many promising renewable energy technologies, such as wind and solar power, but they are not considered cost-efficient compared with already mature technologies (ANRE, 2006). An additional obstacle is that they do not share the favourable institutional setting of the technologies that have been developed for a longer time. Policies are thus necessary in order to overcome institutional barriers, allow the technology to mature and create an initial market (Sandén, 2005).

To design efficient policy instruments, knowledge is needed about what mechanisms hinder the diffusion of the new technology. One method to analyse the development and diffusion of a technological innovation is to investigate its "technological innovation system" (TIS), i.e. what institutions (e.g. regulations, laws and culture) and actors (e.g. governmental bodies, companies and universities) relate to the technology, and what interconnections there are between the different actors. To understand, not only the structure of the system, but what processes that go on inside it, one can analyse its functional dynamics, i.e. look at the key processes that influence the development, diffusion and use of the technology (Bergek et al., 2008). These functions can then be used to assess the innovation system, and determine the key inducement and blocking mechanisms. To determine the performance of a particular technological innovation system, it is particularly useful to compare it in functional terms with a TIS in another country. Some previous empirical studies that have used the technological innovation system approach to study the development and diffusion of PV are Jacobsson and Bergek (2004), Palmblad et al. (2007), Crassard and Rode (2007) and Porsö (2008).

Solar cells, or photovoltaic (PV) cells, transform incoming solar radiation to electricity. The technology has a large potential as a source of renewable energy since the Earth receives many times more energy from the sun than is currently used in the global energy system. It has been estimated that the technical potential of PV is 23 times higher than the present world electricity production (Hoogwijk, 2004). On a world-wide scale, the market is increasing, with a yearly growth of 26 to 46 percent during the last decade, but there are large differences between nations.

Today, Japan and Germany are the leading PV countries in terms of both market size and cumulative installed capacity. Combined, Japan and Germany accounted for about 80 percent of the total PV power that had been installed in IEA PVPS countries[1] at the end of 2006 (IEA-PVPS, 2007). However, compared to other energy sources, PV makes only a marginal contribution to Japanese primary energy supply, which is dominated by oil, followed by coal, gas, and nuclear (see Figure 1).

The goal of this study is to analyse the functional dynamics of the Japanese PV innovation system, in order to understand the historical diffusion of PV in Japan, and more specifically to identify the blocking mechanisms facing the innovation system today, hindering further diffusion of the technology. Key policy issues, related to the blocking mechanisms, will be pointed out, which we hope will contribute to the general understanding of the diffusion of renewable energy technologies. The German PV innovation system has previously been studied by, among others, Swedish innovation system researchers (Jacobsson et al., 2004; Jacobsson and Lauber, 2006), and their results will be used to compare the dynamics of the two innovation systems, and lead to an assessment of the functionality of the Japanese system today.

The study was carried out as a master's thesis for two students at Chalmers University of Tech-

[1]The International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) is an international programme, which aims at increasing international collaboration efforts to accelerate the development and diffusion of PV. Currently, 21 countries, plus the European Commission and European Photovoltaics Industry Organisation are members (IEA-PVPS, 2007).

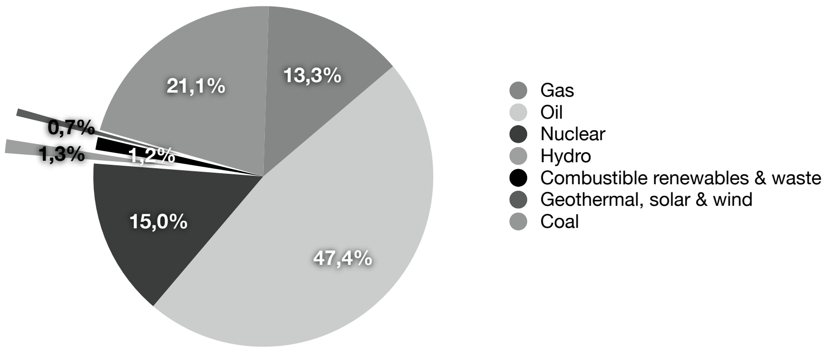

Figure 1: Japanese total primary energy supply, 2005.
Adopted from IEA (2005).

nology, and included a stay for three months as visiting researchers at the University of Tokyo to gather data and perform interviews with key actors in the innovation system. Before going to Japan, a literature study was carried out in order to identify and get a general understanding of the key events and actors in the development of PV since the first oil crisis.

The report is structured as follows. It begins with a description of the analytical framework and method used in the study, and continues with a short description of the technology behind photovoltaic power generation. In the analysis that follows, the historical development in PV in Japan is described and mapped in terms of the seven functions described by Bergek et al. (2008). The development of the German PV innovation system is then described based on Jacobsson et al. (2004) and Jacobsson and Lauber (2006), and used in order to assess the Japanese PV innovation system and identify the main blocking mechanisms. The report ends with a suggestion of key policy issues plus a summary of the conclusions, discussion of the validity of the results and suggestions for future research.

2 Analytical framework

In this section, an overview of the analytical framework – functional dynamics of technological innovation systems – will be given. It will cover the motivation for using the innovation system approach, a definition of technological innovation systems, and the functional dynamics approach described by Bergek et al. (2008).

2.1 Technological innovation system

To analyse the development and diffusion of an emerging technology from a cross-disciplinary systems perspective, the concept of innovation systems has been proposed as a useful tool. This type of system approaches has been put forward since at least 1987 (Jacobsson and Johnson, 2000), by a variety of researchers from different fields. Jacobsson and Johnson (2000) describe this approach as being different from the neo-classical economic approach to analysing innovation, in that it emphasises that:

- "innovation and diffusion processes is both an individual and collective act [of many firms and other types of actors]", and that
- "(...) [there is an] 'innovation system', which both aids and constrains the individual actors making a choice of technology (...)"

Studying innovation from a systems perspective thus highlights the joint action of many actors, and recognizes that the "system" (which has not yet been defined) has an important role in technological choice, and thus large-scale technical changes.

There have been many different suggestions on what level, e.g. national, regional or sectorial, to focus the innovation system (Markard and Truffer, 2008). Depending of the purpose of the analysis, the choice of system boundary or delimitation is very important since it will affect the results and conclusions of the analysis (Markard and Truffer, 2008). An analysis of a national innovation system can for instance be used to analyse the innovative capacity of a country, providing an insight into how the activities on governmental and company level fit together.

One particular innovation system concept that has been suggested in the literature is that of a technological system, which can cross both geographical and sectorial boundaries (Jacobsson and Johnson, 2000; Markard and Truffer, 2008). A commonly cited definition of a technological system is:

> a network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or a set of infrastructures and involved in the generation, diffusion and utilisation of technology (Carlsson and Stankiewicz, 1991).

Since the technological system approach puts the focus on a specific technology, or a range of technologies, several such systems can be found in the same geographical area, and thus compete with each other (Jacobsson and Johnson, 2000). The three elements that are normally included in the technological innovation system concept are actors, networks and institutions, which can be described as follows:

Actors in a technological innovation system consists of the companies that relate to the technology along its entire value chain, universities, research institutes, interest organisations, public bodies, users, etc. (Bergek et al., 2008). The different types of companies can include manufactures of a product that utilises the technology, but it can also be companies further up or down in the value chain, such as suppliers of raw materials or customers.

Networks are the second structural component of a technological innovation system. They are channels for transfer of knowledge and attitudes between actors, and can be both formal or informal (Jacobsson and Johnson, 2000; Bergek et al., 2008). Strong networks in a technological innovation system can aid the diffusion of the technology by identifying new problems, developing new technical solutions and spreading knowledge (Jacobsson and Johnson, 2000).

The *institutions* that are identified in the technological innovation system are laws, regulations, practises and culture, which determine the interactions between different actors, and the norms within the system (Bergek et al., 2008; Jacobsson and Bergek, 2004). They provide the context for the actors, and are important in determining what path the technology takes (Markard and Truffer, 2008; Jacobsson and Johnson, 2000). It is important to remember that the concept of technological innovation systems is only an analytical construction for looking at an emerging technology, and that the non-existence of certain institutions can be equally interesting for the analysis. As described by Bergek et al. (2008) – "sometimes, it is the very lack of institutions that is interesting".

2.2 Functional analysis

To understand the performance of a technological innovation system, i.e. its strengths and weaknesses, one cannot simply look at its structure.[2] One of the main reasons for this is that two systems with different structures could have the same output, implying that there are many "ideal" ways to organise an innovation system for it to perform well. One must therefore look at the processes that goes on within the system itself – the *functional dynamics* of the technological innovation system (Bergek et al., 2008).

It is difficult to finally determine which processes are the most important for an innovation system, which can be seen from the various suggested lists of functions that have appeared in the literature.[3] Drawing from experience and empirical studies, authors such as Hekkert et al. (2007) and Bergek et al. (2008) have defined different, but similar, lists of key functions that an innovation system should fulfil, to perform well.

One specific set us functions is the seven functions defined in Bergek et al. (2008) – 'knowledge development and diffusion', 'influence on the direction of search', 'entrepreneurial experimentation', 'market formation', 'legitimation', 'resource mobilisation', 'development of positive externalities'. These will now be described in more detail.

- **Knowledge development and diffusion**. One of the most important roles of an innovation system is to develop and spread knowledge within the system. This function is an attempt to capture that process. The created knowledge isn't simply fundamental knowledge about the technology itself, but encompass many different categories. Examples are knowledge of production methods, knowledge of utilising the technology in different applications. Quantitative ways of measuring this function is to look at indicators that are related to the creation of new knowledge – patents, R&D projects, published articles etc.

- **Influence on the direction of search**. Influence on the direction of search is a function that captures the perception of the future of the technology, i.e. beliefs about its potential applications and use. This can, for instance, be strengthened by new governmental or public visions of the future, and weakened by new and unexpected problems with implementing the technology. This is difficult to measure in quantitative terms, so one have to resort to qualitative indicators such as belief in growth potential and articulation of demand from leading customers.

[2] This section draws heavily upon Bergek et al. (2008).

[3] For a list of the different sets of functions and a comparison of them, please refer to Bergek et al. (2008).

- **Entrepreneurial experimentation**. For an innovation system to reduce uncertainties about the technology, it is important to experiment with new applications, uses and technologies. This functions measures the degree of experimental activity that takes place in the innovation system – both by new entrants or by established actors, trying new applications and research in new innovative technologies. Entrepreneurial experimentation can be measured in number of new entrants into a technological field and number of new applications that are being researched or commercialized.

- **Market formation** is the function that captures how one or several markets are created for different uses of the technology. The function also relates to how articulated the demand for the technology, and how well one knows the potential or actual buyer of the technology. The importance of this function depends heavily on how far in the development and diffusion the technology has reached; a newly made invention will perhaps only have small "nursing markets", where volumes are small and demand poorly articulated. Quantitative indicators to measure this functions are market size and types of customers.

- **Legitimation** concerns how accepted the technology is by different groups of stakeholders, and how well the technology and relevant institutions fit together. This may be affected by other technological innovation systems competing for the same market, and by the strength of different interest organisations. One way to measure this function is by looking at how well the technology and relevant institutions are aligned.

- **Resource mobilisation** is the process of generating financial and other types of resources for the new technology. Its strength depends on the amount of venture capital that is available, the number of skilled prospective employees, etc.

- **Development of positive externalities**. One of the characteristics of a strong technical innovation system is the presence of free external benefits, such as a skilled labour pool, and knowledge spill-over. This functions captures the process of creating such positive externalities.

The functions are not independent, but can influence each other (Jacobsson et al., 2004). The process of legitimation of a technology can for instance have a large effect on the influence in the direction of search or resource mobilization, which in turn affects entrepreneurial experimentation.

2.3 Assessment through system comparison

At this point, the theoretical framework has mapped both the structure (i.e. actors, networks and institutions) and the dynamics of the technological innovation system (i.e. the seven functions).[4] For the innovation system approach to be of use for policy makers, it is preferable to continue the analysis with an assessment of how well the system is functioning, or in other words to assess the *functionality* of the innovation system.

Various methods have been proposed to assess the performance of a technological innovation system, such as determining the phase of the technology and thus comparing its functional pattern to an "ideal" system in the same phase (Bergek et al., 2008).

The method chosen in this article, is to compare and contrast the functional pattern of the primary system with that of another technological innovation system. The contrasting system should have some similarities, but can be in for instance another geographical area. By a comparison of the functional pattern of the two systems, one may find commonalities and differences, which leads to an assessment of the primary system's performance. The assessment of the functionality will then be a guide in finding inducement and blocking mechanisms of the technology, which in turn can

[4]This section, as well, draws from Bergek et al. (2008).

lead to suggestions of key policy issues.

It is important to remember that the method described in Bergek et al. (2008) is primarily focused on identifying “system failures” or weaknesses, in functional terms, to be of use for policy makers. The assessment can thus be a bit biased towards the negative aspects of the performance of the system. This should not be interpreted as the system being “dysfunctional”, but viewed as an analysis of improvement potential.

3 Method

This study uses the functional dynamics approach of technological innovation systems in order to understand the historical development of PV in Japan, starting from the first oil crisis in 1973, and determine blocking mechanisms for further PV diffusion. The analysis follows the steps described in Bergek et al. (2008), from mapping the structure of the innovation system to specifying key policy issues. This specific method was chosen in order to take advantage of the knowledge that existed at the division of Environmental Systems Analysis at Chalmers University of Technology. An additional motivation was that, although the development and diffusion of PV in Japan had been studied before, it had as far as we know never been analysed using the functional dynamics approach specifically.

Looking at PV in Japan is interesting, since it has been one of the leading countries in recent years, in terms of cumulative installed capacity, market size and production.[5] PV research was also initiated at an early stage in Japan, which makes a historical outlook interesting in order to understand the current situation. The spatial boundary was chosen to be a single country, although many companies and other organisations act on a regional or global level, since many of the relevant institutions (energy policies, regulations, laws, etc.) vary at the country level.

Today, the German market for PV is the world’s largest, after overtaking Japan in 2004. The two technological innovation systems have developed in a similar time frame, but under different conditions, which made the German case suitable as the reference for an assessment of the performance of the Japanese PV innovation system. An additional reason to use Germany was that the case had previously been studied by Swedish researchers using the same analytical framework, reducing the time needed to investigate it. The Japanese case could thus be investigated more thoroughly to give a deeper and more accurate picture.

Qualitative and quantitative data used in the study were collected through a literature study and through face-to-face interviews in Japan. The key actors of the Japanese PV innovation system were identified through a preparatory survey of literature, conference papers, exhibitor list for trade shows, IEA PVPS membership lists, etc. Once in Japan, additional actors were identified through what Bergek et al. (2008) describes as a “snowballing effect”, where interviews with one actor often led the way to new contacts. In total, about twenty different actors were met including manufacturers, architects, university professors, industry organisations, researchers, and users. For a full list of interviews that were performed, see Appendix A.

Besides interviews, a number of events related to PV or innovation, such as “PV Expo 2008” and “4th Workshop on the future direction of PV”, were attended to find new contacts and to complement the mapping of the innovation system. For a full list, see Appendix A.

While performing interviews, open-ended questions were often included to find new angles of approach and key events. In that way, details that otherwise might have been overlooked were found and the analysis was made as complete as possible in the time available. In most cases, double notes were taken of what was said during the interview. The notes were then merged into an interview

[5]Megawatt (MW), instead of monetary value, is used throughout this report as the measure of market size.

transcript within a few days of the meeting, and successively sent to the interviewee for approval and corrections. In some cases, simply a list of quotes that were going to be used in this paper was sent for approval. In the final report, all citations from face-to-face meetings come from such approved transcripts or quotes. If the time frame of the study had been longer, follow-up meetings with the key actors would have been schedules, but this was unfortunately only possible in one case.

After returning from Japan, the gathered data from literature and interviews were organised into events and put on a time axis. Key events were identified depending on the relevance found during interviews, in the available literature, in energy policies, etc., and different functional patterns were found through analysing and discussing the events between ourselves.

The evolution of the German PV innovation system was summarised from articles such as Jacobsson et al. (2004) and Jacobsson and Lauber (2006), and the main differences and similarities between the Japanese case were identified. From this, conclusions were drawn regarding the functionality of Japanese PV innovation system, and blocking and inducement mechanisms were determined, in connection with the relevant functions. Finally, a list of suggested key policy issues were made in connection to the blocking mechanisms.

As this study was carried out as a master's thesis, it was limited to about 20 weeks, out of which three months were spent in Japan. Some delimitations thus had to be made. The first was the exclusion of some interesting actor groups from our interviews. Since some actors groups – such as PV module manufacturers – were more represented than others, there is of course a bias in the historical events that were included. Foremost, this was a consequence of the "snowballing" method used to locate interviewees, where interviewees in one actor group mainly could provide help with contacting additional actors in the same group.

Of the actors that were not available for interviews, the involvement of housing manufacturers, especially designers of prefabricated houses, could have been the most interesting to include. Also, no venture capital firms or investment banks were interviewed, which means that their involvement in the development and diffusion of PV were not known. Additional actors upstream and downstream of the PV value chain would also have been interesting to include. Literature studies were made to compensate for this lack of first-hand data. Additionally, an in-depth patent analysis was not done, something that could have identified additional actors and networks.

4 Photovoltaic power generation

This section gives a short introduction to the technology of photovoltaic power generation, some possible applications and its value chain.

The solar cell, or photovoltaic (PV) cell is a technology that converts incoming solar radiation to an electric current. Unlike solar thermal power, it uses the photovoltaic effect, discovered in 1839 by A.E. Becquerel (Bahaj, 2002). In recent years, the application of PV that has gathered the most attention is for power generation – to use solar cells as a source of renewable energy to replace or complement carbon-dioxide emitting energy sources. A PV system can be either connected to the electricity grid, or used in as stand-alone system ("off-grid application") in places where it is not practically or economically possible to build connections to existing power lines.

Solar cells can be made out of many different materials and through different production technologies, which produce cells with different characteristics. About 90 percent of today's production consists of wafer-based silicon cells (c-Si), which can be divided into mono-crystalline silicon and poly-crystalline silicon cells (Jäger-Waldau, 2007). The knowledge base behind producing this type of cells have many common features with the manufacture of other silicon-based semiconductor components (Nagamatsu et al., 2006). Other solar cell technologies that are either being researched or commercialised include cadmium telluride (CdTe), copper-indium selenide (CIS), amorphous silicon (a-Si) and dye-sensitised cells. A common property of these technologies is that they can be made thinner than conventional solar cells and, as a result, reduce the need for raw materials. A modern solar cell has an efficiency, measured as the percentage of incoming radiation that is converted to electricity, of roughly 10-20%, depending on which technology is used.

To supply electricity to the grid, a number of solar cells are first connected and assembled into a solar module. Several solar modules, together with some additional components, such as inverters, form a PV system. The extra components, sometimes called balance of system (BOS) components, are used to assure a smooth and safe integration to the grid and currently makes up about 20–70 percent of the cost of a PV system (IEA-PVPS, 2007). In the case of off-grid applications, an energy storage system, such as a battery, is often included.

There are thus many categories of companies involved in the manufacturing and installation of a PV system (also see Figure 2):

- Raw material suppliers. Since most solar cells are made out of crystalline silicon wafers, this category consists mainly of silicon raw material miners and companies refining and purifying the material into solar-grade silicon. The output products from this step is usually in the form of silicon ingots or wafers. For other types of solar cells, this category would instead consist of suppliers of gallium, cadmium, etc.
- Cell manufacturers are the companies involved in making solar cells from the raw materials. In some places, it is common that the solar cell manufacturer also handles the module assembly step.
- Module manufacturers take solar cells, connect them and encapsulate them in weather-protecting material. This produces a solar module, which is ready to be used as a part of a PV system.
- Other solar system component manufacturers supply the electrical components and mounting structure that are needed to use the solar module as a part of an electricity-generating system. If the system is connected to the electricity grid, one important component is the inverter, which is used to transform the direct current from the solar cell into alternating current. For off-grid applications, a supplier of storage batteries might also be included in this category.

- Installers and construction companies takes care of the installation and maintenance of a PV system according to the rules and regulations in the country in question. This ranges from architects and engineering firms that design skyscrapers to electricians installing a single PV system on a private home.

These categories are of course not fixed entities and there might be companies that handle several of the steps. One example is Kyocera Corporation in Japan, which have everything from silicon production to module manufacturing in-house. They also handle the final step, which is design, installation and maintenance of PV systems (Ozaki, 2008).

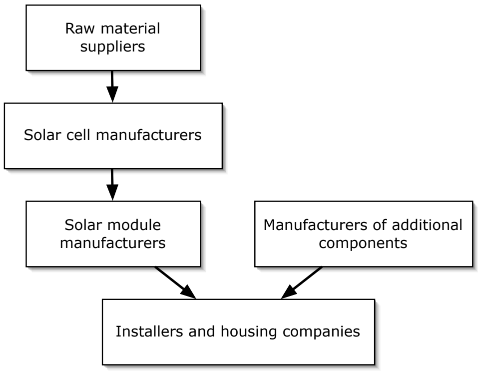

Figure 2: Categories of companies involved in the production and installation of a PV system. Partly based on Kaizuka (2008).

5 Evolution of the Japanese PV innovation system

This section describes the evolution of the Japanese PV innovation system in terms of events and the seven functions described in Section 2.2. The history has been divided into three periods, according to commonalities that were found in the functional patterns of each period.

5.1 Research programme and niche markets – 1973–1985

In 1973, there was an oil crisis where the world market price for oil rose rapidly (Figure 3). Japan was at this time heavily dependent on fuel imports with about 77% of its primary energy coming from oil, and there was a need to ensure a long-term stable energy supply (NEDO, 2007). As a response, the Japanese Ministry for International Trade and Industry (MITI) launched a national research and development (R&D) programme for a range of alternative energy carriers the following year – the "Sunshine Project".[6] The oil crisis had spurred a strong political and public support for the programme (Kimura and Suzuki, 2006), which gave a positive effect on the 'legitimation' of non-oil energy carriers.

The origin of the programme was a proposal on R&D for solar energy, but the final plan included coal gasification/liquefaction, geothermal and hydrogen as well (Kurokawa, 1994; Kimura and Suzuki, 2006). The programme had a long-term goal to develop non-oil energy sources so that they could provide a significant contribution to the energy mix in the year 2000 (Kimura and Suzuki, 2006). Most MITI projects at this time were for 5 years, but the Sunshine programme got a long-term goal of 25 years, due to the long time needed to put the technologies into practical use (Kurokawa, 2008; Kimura and Suzuki, 2006). This long-term goal influenced the 'direction of search' for alternative energies, as they were believed to play a role in the future energy system.

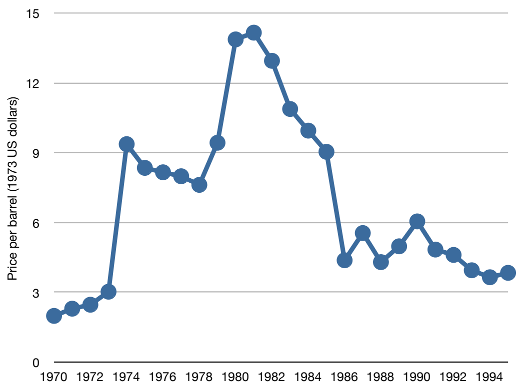

Figure 3: Oil price adjusted for inflation, 1970–1995. The 1973 and 1979 crises are apparent. Data from OECD (2007).

Before the oil crisis, a small number of Japanese companies such as Sharp, had already started PV R&D, and used it in some off-grid applications, such as satellites and lighthouses (Tsujimura and Matsushita, 2008). Watanabe et al. (2000) describes the aim of PV development under the Sunshine programme as:

- "encouraging broad involvement of cross-sectorial industry"
- "[...] stimulation of cross-sectorial technology spill-over"
- "inducing vigourous industry investment in PV R&D"

[6]Other names that can be found in literature are "Sunshine Program" and "Sunshine Plan", possibly due to the translation possibilities of the Japanese word *keikaku*, which can refer to a project, scheme or plan.

In terms of functions, this implies 'knowledge development and diffusion' in firms from different industries and 'development of positive externalities' through cooperation, and the encouragement of knowledge spill-over. No evaluation has been found whether these goals were achieved, but it can be noted that in 1975, Sanyo Electric started PV R&D, and that Kyocera, together with Sharp, Mobile Oil, Tyco Laboratories and Matsushita Electric Industrial Corporation started the Japan Solar Energy Corporation (JSEC) as a joint venture for PV R&D (Sanyo, 2007; Ozaki, 2008). Ozaki (2008) points to this collaboration as leading to the clustering of crystalline silicon PV manufacturers that can be seen in the Kansai area, indicating the 'development of positive externalities'.

PV was included from the beginning of the Sunshine project, but accounted for only a minor part, with solar research mainly focused on solar thermal applications and solar thermal power generation (Kurokawa and Ikki, 2001).[7] In fact, the initial inclusion of PV was not obvious, as a person involved in the project from an early stage describes:

> It was a young colleague in MITI who quietly added one line about PV in the [Sunshine project] proposal (Kurokawa, 2008).

Solar thermal power became the technology of choice, due to its lower cost, but possibly also because the technology had been developed in other places (Saitoh, 2003; Kimura and Suzuki, 2006). This indicates a belief that solar thermal power was closer to the market than PV, which would suit the goal of the programme better. PV cost targets were made early on in the project for 25 years in the future (Kurokawa, 2008). Kimura and Suzuki (2008) describes the cost-curve during the 1970s as being "prepared by manufacturers, since MITI didn't have the expertise [at the time]". The addition of cost-curves influenced the 'direction of search' towards PV at a time when knowledge of the technology was low, and it benefited from the general 'legitimation' process of non-oil energy technologies.

Despite its relatively low level, the early governmental support for PV research was important to 'mobilise resources' at a time when the price for PV was very high, and activity quite low. The added funds helped spark the interest for PV in companies (Kimura and Suzuki, 2006) leading to increased 'entrepreneurial experimentation' and 'knowledge development and diffusion' at a relatively early stage.

In the first few years, PV research in the Sunshine programme was focused on fundamental research on photovoltaic cells, but in 1978, research into PV systems technologies was initiated as well (Kurokawa, 1994). Kurokawa (1994) describes the grid connected roof-mounted systems as being "the major target from an early point of the R&D", due to the extensive electricity grid in Japan. Additionally, the high cost for usable land in Japan makes rooftops an attractive location to install PV (Kurokawa and Ikki, 2001). Before this new area of research, it was "inconceivable" that that distributed PV generation could replace conventional energies (Kurokawa and Ikki, 2001), but the research into system technology set a new future application of PV, and thus influenced the 'direction of search'.

There was a second oil crisis in 1979, and the oil price rose rapidly (Figure 3). The response of MITI was to increase budgets and installation targets for the Sunshine programme (Kimura and Suzuki, 2006). A recommendation to MITI from the Industrial Technology Council was that PV should be one of the R&D areas to get priority (Watanabe et al., 2000), and governmental PV R&D can be seen to increase between 1979 and 1980, even though solar thermal expenditures still remained larger (see Figure 4).

[7] "Solar thermal power" is an alternative technology for converting solar radiation to electricity that, unlike PV, uses water or another liquid or gas as an energy transport medium (WEC, 2007).

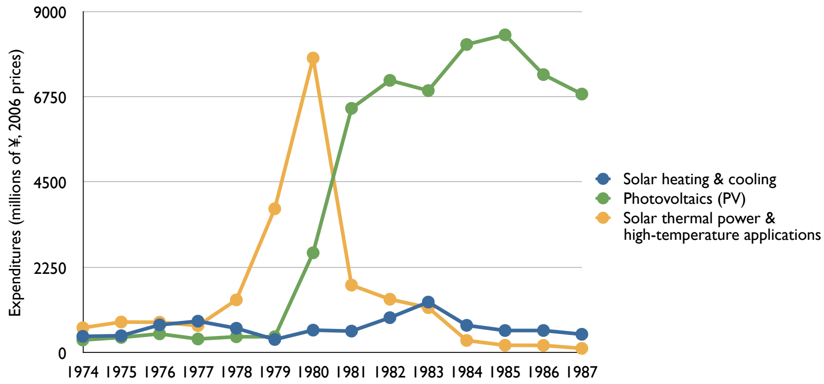

Figure 4: Governmental RD&D expenditures for solar energy in Japan, 1974–1987. Data from IEA (2008).

In the policy response from MITI, there was also the enactment of the "Alternative Energy Law"[8] (Jäger-Waldau, 2007). This law led to an increased electricity tax and introduced a "special account" for alternative energy development, from which the main part of the budget of the Sunshine programme came during the following years (Kimura and Suzuki, 2006).

Around this time, two Japanese test plants for solar thermal power failed to show attractive results due to the unstable weather in Japan (Kurokawa, 2008).[9] The government thus gave up on solar thermal power, but, according to Kimura and Suzuki (2006): "the solar energy division of MITI did not want to cut their budget". In 1981, the governmental R&D budgets were thus shifted to PV, as it was a "good alternative to succeed the budget" (Kimura and Suzuki, 2006).

The combined effect of increase in budgets for new energy sources, and the, quite lucky, shift in budgets from solar thermal to PV contributed to an increase in governmental RD&D for PV, which increased by 15 times (in real terms) between 1978 and 1981,[10] which can be seen in Figure 4. Watanabe et al. (2000) notes that the increase in governmental expenditures was followed by an increase in effort from eight leading PV firms in the Sunshine project, leading to what is described as "vigorous industry R&D". In total, this meant that 'resource mobilisation' of PV was increased dramatically between the oil crisis and the early 1980s, even though there was no significant 'market formation'.

The stable source of funding is described by a number of people as an important point for PV development in Japan (Kurokawa, 2008; Kimura and Suzuki, 2006). It provided a "stable environment for research communities" (Kimura and Suzuki, 2006), pointing to 'influence on the direction of search'.

The Alternative Energy Act also meant the establishment of a new body responsible for energy R&D – the New Energy Development Organisation (NEDO) (Watanabe et al., 2000). NEDO took over the responsibility for research and promotion of "new energy"[11] from MITI. The establishment of a separate organisation for handling new energy development indicates that a strengthened 'legitimation' of new energy technologies, including PV.

[8]This law is also known under the name "Law Concerning the Promotion of Development and the Introduction of Oil Alternative Energy" (Jäger-Waldau, 2007).

[9]Solar thermal power requires direct insolation, and the power output goes down to zero when a cloud pass by (Kurokawa, 2008).

[10]Calculated from R&D data from IEA (2008), with fixed 2006 prices.

[11]"New energy" appears to be a more commonly used expression in Japan than "renewable energy" in energy policy statements. New energy is a broader definition, which includes energy from waste, etc. (ANRE, 2006).

The price of oil dropped in the early 1980s (Figure 3), which led to a lowered attention to alternative energy development in Japan (Kimura and Suzuki, 2006). Despite this, the R&D expenditures for PV were kept at a fairly stable level from 1981 onwards (Figure 4). In terms of functions, the decrease in attention for new energies can be described as weakened 'legitimation' of these technologies, including PV. An indicator of this is the lack of governmental policies regarding PV in the 1980s when not much happened in terms of policy – a fact also pointed out by Gonnermann and Iida (2007).

At this point, the lack of market and lowered attention of PV could have caused Japanese companies to loose interest, and focus their efforts on the development of other, more lucrative semiconductor applications. Kimura and Suzuki (2006) writes that this did happen for some actors, such as Hitachi, NEC and Toshiba in the late 1980s, while other companies stayed. Some of the reasons that have been pointed out was "commitment from top-level management" (Kimura and Suzuki, 2006) and "belief in the future of PV" (Ozaki, 2008), but there was also the creation of a new market for PV – small scale electronics, starting with calculators in 1980. This led to 'market formation' of a small, but important market for PV.

Summarising the period, an oil crisis lead to the start of an initial governmental research programme, that increased 'resource mobilisation' and 'legitimation' of PV. This led to new entrants, and increased 'entrepreneurial experimentation', but yet no 'market formation'. The start of PV system research strengthened the 'influence on the direction of search', where PV could be seen as a competitor to conventional electricity. The successive drop in oil price led to a decrease in 'legitimation' of PV, but some companies still stayed in the sectors due to the 'market created' by consumer electronics. Research budgets were kept quite high and stable, but there was no large markets for PV systems for power generation.

5.2 Regulation changes and market take-off – 1986–1998

At the start of this period, PV had a small market in the form of small scale electronics, but did not gather too much attention. While driving factors for solar technology in the previous period was dominated by high oil prices, a decreasing interest could be seen globally (Smil, 2003) as well as in Japan (Kimura and Suzuki, 2006) as explained in the last section. Also, as seen in Figure 5, when the share of oil in the Japanese electricity mix decreased, it was replaced by nuclear power and liquified natural gas (LNG), and later coal as well.

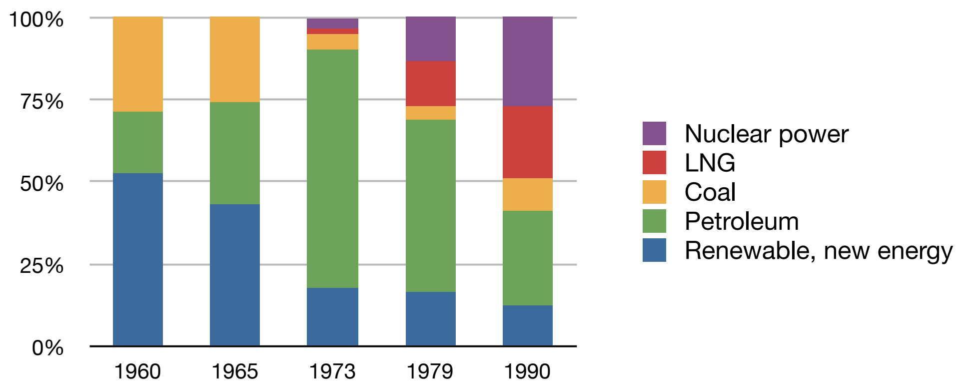

Figure 5: Evolution of Japan's energy mix, 1960–1990.
Adopted from METI (2006*a*)

The networks of aggregated PV systems conceived in the late 1970s were hindered by regulation barriers and low interest by the electrical utilities. They were still reluctant to accept PV into their electricity grid, claiming that solar power generation was unstable, which would not work well with their mission to provide stable electricity (Kimura and Suzuki, 2006). In 1986, an important NEDO demonstration project for creating legitimacy for PV amongst utilities started. The project was aimed at system demonstration by constructing one hundred 2 kW grid-connected systems at the Rokko Test Centre for Advanced Energy Systems. As a result of the successful end of the field-testing in 1990, grid-connection was gradually accepted by the electrical utilities (Kurokawa, 2008).

In the beginning of the 1990s, there was also development in making simplifications of various laws and regulations concerning PV installation. Before 1990, installing a residential PV system required the same qualifications as for a large-scale coal power plant (Kimura and Suzuki, 2006). Kimura and Suzuki (2006) describe this process of simplifying regulations as being run by a single person within METI, who worked with creating legitimation for the technology by writing articles in big newspapers. Also of high importance was the changing of laws regarding utility connection in 1992 (Kurokawa, 1994).

Following these processes and projects, a "Field Test Program" was started in 1993 (JPEA, 2008). The same year, utilities voluntarily decided to introduce a net-metering programme, in order to comply with the new national PV targets, but also to avoid regulations (Kimura and Suzuki, 2006). Costumers could with this system sell back electricity through their grid-connected PV system at the same price as the grid-price. The year after, the "Guideline to Regulate Utility-Connection Technology" was changed to permit a reversed power flow into the net (Kurokawa and Ikki, 2001).

Parallel to these two legitimation processes related to tests and regulation, another began as an initiative from the PV companies themselves. As discussed in the previous section, markets for PV were small. The pocket calculator market – the largest market for PV in the early 1980s – was becoming saturated (Kimura and Suzuki, 2006). Governmental funding was aimed at R&D, and while many companies had technology ready for mass-production,[12] there was no market. Companies from many different fields thus gathered to create an industry organisation, the Japan Photovoltaic Energy Association (JPEA) in 1987. Already from the start, it tried to change the money flow from R&D to market support – "We visited the governmental offices to discuss the need of a market to cleverly utilise the technology. We also participated in drafting METI's picture of field-test and rooftop programmes." (JPEA, 2008).

A fourth 'legitimation' process for PV in Japan also manifested itself in the end of the 1980s. In this period, the issue of global warming emerged on the global political arena, with many international conferences. As described by Kimura and Suzuki (2006), the conference in Toronto 1988 called for 20% reductions world-wide, though it was not legally binding. The Ministerial Conference on Air Pollution and Climate Change in Noordwijk 1989, was a first attempt to make a major multilateral agreement on freezing CO_2 emissions on the 1988 level. Effects in Japan can be seen in the forms of a new minister and ministerial council on global environmental conservation. Also, in the MITI Energy Outlook in 1990, ambitious targets for PV installation were included. By the year 2000, 250 MW was to be installed, and 4,600 MW by 2010.[13] This is explained by Kimura and Suzuki (2006) as a way to for MITI to avoid inconsistency between talks of stabilisation of greenhouse gases and the actual Japanese energy mix.

The Chernobyl nuclear accident occurred in 1986, and brought on changes in energy policy throughout the world, but does not seem to have had an long-term impact on Japanese energy policy. As an example, the Japanese nuclear R&D fell 63% in 1986–1988, but in 1989 it was above the 1986 level (IEA, 2008). As a contrast, Germany decided to phase-out its nuclear power, which was a very important for further legitimising renewables, as shall be described in Section 6.1. PV field-testing also started in Europe (JPEA, 2008).

[12] NEDO research into c-Si and a-Si manufacturing technology had started already in 1980 (Hashimoto, 2003).
[13] The target for 2010 was rewritten in the 1994 Energy Outlook to the current goal of 4,820 MW.

There were also changes in how knowledge was developed and diffused within the system in this period. In 1990, NEDO went through a reorganisation (Imoto and Ishimura, 2008). The same year, the Photovoltaic Power Generation Research Association (PVTEC) was initiated. It was a research consortia with a wide range of companies, from textiles to oil (Watanabe et al., 2000). It aimed at managing PV projects on low-cost mass production, high efficiency solar cells and BIPV modules (Kurokawa and Ikki, 2001). Overall, an increased activity among PV companies can be seen at this time: Kaneka switched from consumer applications to power applications in 1992–1993 (Yamamoto, 2008). Also, Honda "started thinking about PV" at this time, after winning a solar car competition though they didn't enter the market until 2008 (Matsuura, 2008).

In 1993, the Sunshine Programme merged with the "Moonlight Program"[14] and the "R&D Project on Environmental Technology" to form the "New Sunshine Project" (Dooley, 1999). The new programme now composed of four parts: renewable energy development, high efficiency utilisation of fossil fuels and energy storage, and lastly international energy cooperation (Hamakawa, 1994).

All these factors may have revitalised PV in Japan and contributed to an increased long-term legitimation of PV. However, at the time, things were tough, as explained by an interviewee:

> In 1994, people didn't understand why we needed PV. Maybe, some people believed PV [was] useless (JPEA, 2008).

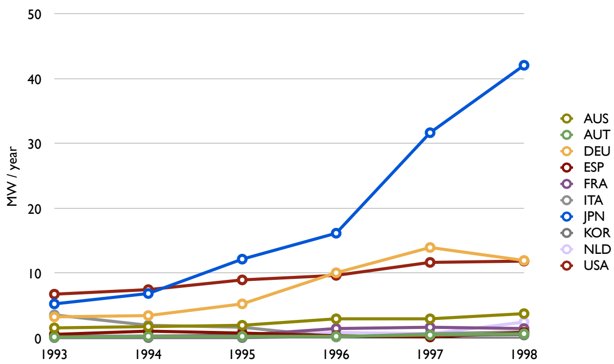

Figure 6: PV market in selected IEA PVPS countries, 1993–1998
Compiled from data in IEA-PVPS (2003).

In this year, a programme called the Residential PV Monitoring Programme was started, by MITI, under operation by the New Energy Foundation. It was aimed at subsidising PV systems in residential homes. It was requested that the installer monitored the performance of the system to gather data (Kurokawa and Ikki, 2001). In 1997, this programme was changed into a Residential Dissemination Programme. The governmental target was set to keep a stable price of 2 million yen for a 3 kW PV System, which at the time cost about 6 million yen (JPEA, 2008). However, as explained in an interview: "There was no relation between [the price of a PV system] and the grid electricity cost" (JPEA, 2008). Neither does this price seem to be directly connected to the policy goals of PV introduction, in the sense that it was instead constructed to keep the price at a stable level. The subsidy was to be removed when the target price was reached, i.e. not when the target installation was reached, and the Japanese market was "self-sustained" (Kimura and Suzuki, 2006).

In terms of 'market formation', the programme was a success. Market for PV in Japan took off compared to other countries, as can be seen in Figure 6. Between 1993 and 1994, the price of a 3

[14] The "Moonlight programme" was an R&D programme on energy conservation technologies, which started in 1978 (Hashimoto, 2003).

kW PV system dropped from 11 million yen to 6 million yen, mainly due to reduction of cost for balance of system (BOS) components and mass-production (Kurokawa and Ikki, 2001). Due to the increase in residential grid-connected systems, we can see a shift in the cumulative installed capacity in different sub-markets, from off-grid non-domestic to grid-connected distributed between 1992 and 1999 (Figure 7).

In summary, we can see four parallel 'legitimation' processes in this period. Three were a result of work within the country – the system demonstrations that aimed at showing the stability of aggregated systems, the process of simplifying regulations and the founding of a PV industry association. The fourth was an external process – global initiatives to lower green house gas emissions. Together, these lead to regulation changes, national targets for PV introduction and a market diffusion programme. 'Entrepreneurial experimentation' was increased as NEDO started funding new technologies. Large markets in form of grid-connected residential PV were formed by subsidies.

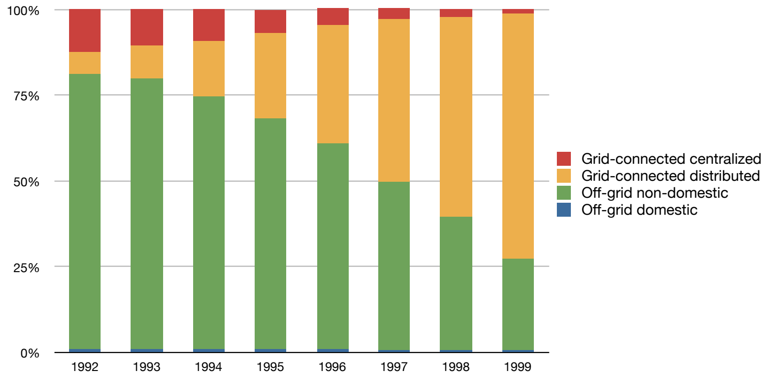

Figure 7: Cumulative installed PV in four sub-markets in Japan, 1992–1999. Data from Shino and Ikki (2003).

5.3 Less market support and international market growth – 1999–2007

In 1999, Japan was the world's leading PV country in production (85 MW/year), cumulative installed capacity (205 MW, or 1.63 W/capita), and market size (72 MW/year) (IEA-PVPS, 2000). The technology enjoyed a certain amount of legitimacy, strengthened by the removal of technical barriers and regulations, the creation of an industry association, global warming concerns, and the market created by the Residential Dissemination Programme. Many companies, from different industrial sectors were involved in NEDO projects, seen in the membership list for PVTEC, leading to 'knowledge development and diffusion'.

Between 1999 and 2003, there was a range of reorganisations of key actors in the PV innovation system: MITI was reorganised into the Ministry of Economy, Trade and Industry (METI), NEDO was reorganised into an administrative agency and 15 research institutes under the Agency of Industrial Science and Technology ("old" AIST) were joined into the National Institute of Advanced Industrial Science and Technology ("new" AIST).

The restructuring of MITI and elimination of the old AIST meant the end of the New Sunshine Programme in fiscal year 2000, which NEDO replaced by a five-year master plan for further PV research (Hashimoto, 2003). At this point, there was no longer-term goals for PV research, which could have led to a setback in the 'influence on the direction of search'. As a researcher at AIST points out regarding the restructuring:

> Before, we got budget directly from METI, which made AIST more independent in choosing topics. Now, we get the budget from NEDO, which has specific goals [...] and we have less freedom. Research work is difficult; sometimes ideas don't work. We would like to spend 1-2 years of trial and error on new ideas. Now, once we propose and receive money, we have to follow the plan, and projects have to be more 'realistic'. (Niki, 2008)

Luckily, a university professor working within PV systems research, noticed the lack of long-term plans and took the initiative to create a new one towards 2030 (Kurokawa, 2008). This eventually became the PV Road map toward 2030, more commonly known as "PV2030", which was adopted by NEDO in 2004 (Kurokawa, 2008). PV2030 is a a long-term projection of the cost reduction of PV, which specifies R&D effort required to be competitive with the cost of electricity for industry in 2030 (NEDO, 2004). The road map specifies that an installed capacity in the range of 100 GW and a full-scale market for PV systems is possible for 2030, and that "it is crucial that PV power generation gains public awareness and confidence in this period" (NEDO, 2004). The plan does not mention any market support policies, regulation changes or changes in behaviour required for the diffusion of PV.

Parallel to the reorganisations and the PV2030, there were interesting activities on the energy policy side. Believing that Japan was behind other countries in energy policies, there was an attempt to introduce a feed-in-tariff (FIT) system[15] in Japan through legislation in the Diet. Such a system would have two main differences to the net-metering and buy-back programme that already existed in Japan: First, the FIT would be a law instead of a voluntary programme. A voluntary system can, at least in theory, be cancelled at any time by the electrical utilities, while a FIT would guarantee the purchase of excess electricity for a longer period. The second difference would be that the buy-back price for a FIT is set at a higher level than the electricity price, while the existing net-metering/buy-back system in Japan implies selling electricity at grid electricity price. A higher rate for the PV installer, would of course shorten the pay-back period of a PV system.

Many Diet members from different parties joined the FIT movement called the "Federation of diet members for promoting natural energy" (Gonnermann and Iida, 2007). According to the proponents, the key elements that caused the failure were the opposition of METI and the electrical utilities (Gonnermann and Iida, 2007).

After the attempt to introduce a FIT failed, METI's proposal of a Renewable Portfolio Standard (RPS) Law[16] passed instead, and came into effect in April 2003(Gonnermann and Iida, 2007). The RPS target is set by METI, and currently specifies that 12.2 TWh should come from new energy sources in 2010 (RPS, 2008). With the expected increase in electricity use, this is estimated to constitute 1.35 percent of the national electricity supply in that year.

Several people related to PV point to this target being too low, or that it only favours the current cheapest technology, and thus not providing an incentive for PV diffusion (Tsujimura and Matsushita, 2008; Kurokawa, 2008; Gonnermann and Iida, 2007). Actually, the aim of the RPS law, is not to increase the diffusion of renewable energy, but to:

> take measures relating to the use of new energy by electricity retailers *in order to enhance the stability of energy supply* [emphasis added], thereby contributing to environmental conservation and furthering the overall healthy development of the national economy (RPS, 2008).

[15]The German-style feed-in-tariff for renewable energies aims to promote the diffusion of renewable energy sources by offering a fixed price – higher than the electricity price – for renewable energy inserted to the grid. The feed-in-tariff is guaranteed for a fixed number of years, making it possible for the end customer to view PV as a financial investment.

[16]The RPS is a green certificate system, where electrical utilities are required to purchase certain fraction of electricity from new energy sources to avoid a fine.

The goal of a law influences the 'direction of search', since it specifies what the most important aspect is – in this case energy stability, which in turn should lead to secondary benefits in areas such as environment and national economy.

Another point of criticism of the RPS system is that the consequences of non-compliance are too weak (Gonnermann and Iida, 2007). If quotas are not fulfilled, METI may issue a deadline for improvement, and if there is not improvement, the maximum fine is 1 million yen (Gonnermann and Iida, 2007; RPS, 2008). In terms of functions, this chain of events can indicate low 'legitimation' of the PV innovation system and other renewables.

At the start of the century, Japan had a programme that provided market support for PV – the Residential PV Dissemination Programme – and the Japanese residential PV market was the world's largest. Over the years, the subsidy level was gradually lowered, and the programme was due to end when the Japanese market was self-sustained and the target cost of a PV system was reached (Kimura and Suzuki, 2006). After the target cost was reached by a top-runner in 2002, the subsidy was greatly reduced and the programme eventually ended in October 2005 (Kimura and Suzuki, 2006; IEA-PVPS, 2006). In the last year, the subsidy was only 20,000 yen/kW, but it has been suggested that the governmental display of support for PV was more important in the eyes of the public than the financial contribution (Kushiya, 2008). When asking interviewees about why people bought PV during the Residential Dissemination Programme, it is often suggested that people in Japan are very environmentally conscious, but are unable to point to any studies or market research results that show this. Kimura and Suzuki (2006) point to two surveys performed 1996 and 1998, that show that people buying PV have above average incomes and have an above average concern for environmental issues. Tsujimura and Matsushita (2008) summarise the Japanese market after the end of the Residential Dissemination Programme as "People only buy PV for emotional reasons, since there is currently no economic reasons."

The end of the Residential PV dissemination programme coincided with a rapid growth of the world PV market, especially in Germany, and Japanese PV manufacturers turned to export (Kurokawa, 2008). This can be seen in the PV market in Japan, which has levelled off since the end of the residential dissemination programme (Figure 8). The only major exception that has been found to this is Honda, which entered the PV market with CIS modules in 2007. Their initial focus is the Japanese residential PV market as they "want their [the customers] feedback and learn for further improvement" (Matsuura, 2008). The international focus of manufactures affects the 'market formation' in Japan.

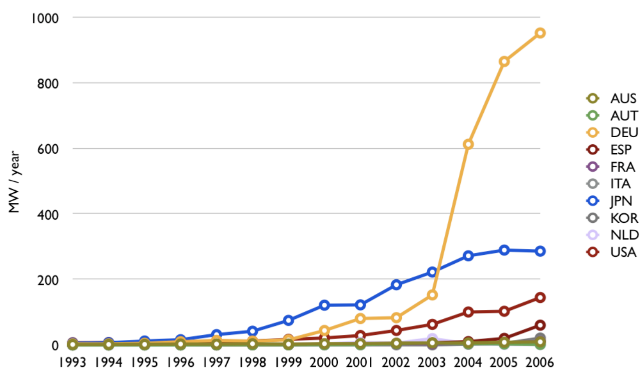

Figure 8: PV market in selected IEA PVPS countries, 1993–2006
Compiled from data in IEA-PVPS (2003) and IEA-PVPS (2007).

Uncertainties regarding technical barriers of large-scale PV introduction such as islanding[17] remained, and a NEDO test project was launched to study this and other effects – the "Demonstrative research on clustered PV systems" project. Between 2002 and 2007, a total of 553 PV systems were installed in a residential area in Ota City. A person involved in the projects comments that:

> Other countries are very interested in the results of this projects, but I have never heard of similar projects overseas. In the EU, there is a 'PV upscale project', with discussions, but no field-testing. (Nishikawa, 2008)

According to Nishikawa (2008), the electric utilities are concerned about islanding in Japan, where the grid historically has been very reliable. "[They] have to follow strict regulations on frequency and voltage fluctuations, because of high demands from customers" (Kushiya, 2008). An "artificial growth cap" has been imposed on wind power (Gonnermann and Iida, 2007) by the electrical utilities in many regions of Japan, due to islanding concerns (Nishikawa, 2008). This can be seen as a lack of 'legitimacy' of distributed electricity generation that don't seem to exist, or at least not be as much of a concern, elsewhere. It also influences the 'direction of search' of PV, since grid stability concerns could possibly be used to limit PV diffusion as well.

Another important theme during this period was the increased competition for silicon feedstock with other technologies, which resulted in a 20% increase of price of solar grade silicon from 2005 to 2006 (IEA-PVPS, 2007). Since crystalline silicon is the main technology used in commercial solar cells, it may have affected the types of solar cells being researched and produced, thus influencing the 'direction of search'. According to IEA-PVPS (2007), Japanese solar cell production only reached 76% of its module producing capacity in 2006. Although this has not been studied in detail, the silicon shortage may have stimulated 'entrepreneurial experimentation' and 'market formation' for non-silicon technologies, indicated by the commercialisation of CIS cells by Showa Shell Sekyui in 2005 and Honda in 2007.

Environmental issues, and especially global warming, continued to get attention throughout the period, strengthening 'legitimation' of renewable energy sources. The Kyoto protocol commitment period starts in 2008, and in May 2007, the prime minister of Japan, Shinzo Abe, made a speech that attracted attention. Introducing the "Cool Earth 50" concept, he stated that world-wide greenhouse gas emissions should be cut by 50 percent in 2050 (Abe, 2007). Cutting costs and increasing efficiency of solar power was mentioned as one of the components of the long-term strategy, together with introducing a non-tie dress code during summer. In the summer of 2008, Japan will host the G8 summit, and many seem to expect an announcement of additional measures on PV before then.

In summary, the period initially saw a strong demand for PV created through the 'market formation' caused by the ongoing residential dissemination programme. 'Legitimation' was fuelled by the ongoing debate about environmental issues, and in particular, global warming, but not strong enough to influence the institutional framework to introduce the next step in market support policies. The attempt to introduce a feed-in-tariff failed, and an RPS system, which can be considered unfavourable for PV, was introduced instead. Reorganisations temporarily led to shorter-term plans by important actors, and the silicon shortage affected the 'direction of search' and possibly 'entrepreneurial experimentation' of new technologies. Markets abroad became more important after the end of the residential dissemination programme.

[17] "Islanding" is a grid instability effect that can occur if a circuit with a large number of PV systems is disconnected from the rest of the grid, which can cause adverse effects (Kitamura et al., 1993). Nishikawa (2008) described the effect as "very unlikely".

6 Assessment of the Japanese PV innovation system

The evolution of PV in Japan has now been described in terms of the functional dynamics of its innovation system. To assess the performance of the innovation system, the development of a corresponding system – the PV innovation system of Germany – will be described in this sections. This shall then be used to find common features and differences, which in turns leads to blocking and inducement mechanisms for the diffusion of PV in Japan.

6.1 Evolution of the German PV innovation system

This section is based on the analyses and conclusions of Jacobsson et al. (2004) and Jacobsson and Lauber (2006).

Research in solar cells in Germany began in 1960, and was greatly expanded after the first oil crisis, when German green movements caused government to start funding solar cell R&D. This funding was kept stable for many years. It was directed into different technological branches, and 'entrepreneurial experimentation' was done with different cell technologies. The solar cell proponents quickly gathered in different ways, first in 1975, when the German Society for Solar Energy (DGS) was established. It was a broad organisation which included members of the public. Another organisation of this type is Förderverein Solarenergie, created in 1986. In 1975, the German Solar Energy Industries Association (GSEIA) was created, and Eurosolar, an organisation to lobby within the political structure was created in 1988. The existence of these organisations are emphasised by Jacobsson et al. (2004) as being of high importance for the processes of creating 'legitimacy' for solar energy, and in turn, institutional change.

In 1983, the first German PV demonstration project took place. It was followed by other demonstration programmes and accompanying monitoring programmes. One of the plants were built in cooperation with a utility. This events are described as effective as means of "creating application knowledge" (Jacobsson et al., 2004). However, there were no incentives to expand markets.

The Chernobyl accident in 1986 lead to dramatic changes in German energy policy. The same year, a five year study was finished and published which concluded that "only reliance on renewables and efficiency would be compatible with the basic values of a free society, and that this would be less expensive than the development of a plutonium-based electricity supply" (Jacobsson and Lauber, 2006). The leading party decided to dismantle nuclear power. It was followed by programme for wind energy and a new solar cell programme – the 1,000 roofs programme – in 1990.

In 1990, the stock of installed PV was only 1.5 MW, and the yearly diffusion was 0.59 MW. Though production was up by a little bit thanks to these institutional changes, when the 1,000 rooftop programme ended, there was no federal programme to continue expansion, and growth was not self-sustained.

A cost covering feed-in law was proposed by PV organisations in 1991, with the help of small-scale hydro, wind turbine owners and Eurosolar. It was passed by an all-party consensus, giving 90% of market price for electricity that was fed into the grid, which was above the level of avoided cost for wind. For solar it was not good enough for increased diffusion. The stated principle behind the new law was to level the playing field for renewables by setting the tariff at a level so that the external costs of conventional power generation was taken into account. The law was designed to introduce a few hundred megawatts of small-scale hydro, so even though utilities were against it, the passing of the law was not a big concern to them, due to the small scale of the project.

Förderverein Solarenergie proposed in 1992 that higher prices in the feed-in law should apply locally for solar power. They worked together with Eurosolar and local organisations to influence local governments. This proved successful, and Aachen was the first city to implement this in 1994. The "Aachen model" became well-known, and many other cities followed. As an effect, the market did not completely disappear after the end of the 1,000 roofs programme. Lobbying was also done at a national level, to introduce a mass-market for solar cells. One example of this is a 100,000 roofs programme, proposed by Eurosolar in 1993.

The feed-in law was not liked by the utilities, who started to lobby against it. For a couple of years, there was talk of amending the law, leading to much insecurity among investors in wind. When a governmental proposal to reduce feed-in rates was put forward in 1997, "massive" demonstrations by solar and wind organisations together with church and farmer groups took place. A committee was enacted to investigate the matter, where 8 out of 15 voted against the proposal. Jacobsson and Lauber (2006), in describing this process, state that "clearly, the new technology had now acquired substantial legitimacy".

The solar power lobby increased efforts. The firm ASE threatened to move production out of the country as there was no market. When promises of a future programme came, major capacity increases took place as companies decided to build factories in Germany. The future programme was the 100,000 rooftop programme, decided by the new coalition in 1998 and implemented in 1999. It included investment subsidies and low interest rates.

The next question was how to revise the feed-in law. The Greens wanted to take the local projects to a federal level. They involved solar cell producers, industry organisations, a trade organisation and federal politicians. They also got support from the Social Democrat Party (Sozialdemokratische Partei Deutschlands, SPD) but for other reasons. The liberalisation of the electricity market caused concerns among the SPD party, and they feared that it would lead to a decline in the energy sector. Especially important was to protect the growing wind power industry. Supporting the Green initiative was a way to accomplish this.

In 2000 the feed-in law was revised. Pay-back rates were fixed and guaranteed for 20 years, i.e. not related to market price as before. In this way, solar cells became an interesting investment option. The results of these institutional changes can be seen in Figure 8 – a major market expansion.

6.2 Assessment through system comparison

Common features and differences between the development of PV in Japan and Germany are here structured into five themes. Each theme will also be explained in terms of functions, aiming at assessing how well different functional processes are performing. In the end of each theme, blocking and/or inducement mechanisms for the functional dynamics of the Japanese PV innovation system will be summarised.

One should remember that, as described in Section 2, the analytical framework puts the focus on the negative aspects of the performance of a system, since this is more useful for policy makers. The reader should not draw the conclusion from this assessment that the Japanese PV innovation system is dysfunctional as a whole, but view this simply as an analysis of improvement potential.

6.2.1 Long-term plans, R&D and commercialisation

In both countries we have seen a stable governmental funding, and in the Japanese case we have also seen that it triggered corporate funding. This long term support is seen as essential by researchers (Jacobsson and Lauber, 2006; Jacobsson et al., 2004) and interviewees (Kurokawa, 2008). It has provided security for researchers as different technological pathways need to be explored. Jacobsson et al. (2004) mentions a case were a company had done research in a technology that

10 years later proved to fail. Kurokawa (2008) points out that also long-term plans are important for recruitment – “Normally, projects last for five years. This is not sufficient for attracting young people” – indicating their role for ’resource mobilization’.

An important inducement mechanism for PV in Japan is therefore the long-term R&D plans and projects that started appearing shortly after the first oil crisis. Similar to the German case, this has generated a momentum of the innovation system through the knowledge and the know-how of actors that has been created. An R&D plan with price targets has been made until the year 2030, which has positive effects in the ’influence on the direction of search’ and ’legitimation’ functions. It has also affected the ’development of positive externalities’, since the NEDO projects have worked as a good platform for different actors to share knowledge.

In Japan, a large-scale commercialisation of PV can be seen after the regulation changes and market support programmes that took place in the 1990s. This decade of commercialisation has generated know-how in companies regarding solar cells, providing benefits to the ’knowledge development and diffusion’, and ’influence on the direction of search’ through investments in certain technologies and applications. As pointed out before, the long-term commercialisation of c-Si solar cells may also have supported the ’development of positive externalities’, since many companies with this technological capability have tended to cluster in the Kansai region of Japan.

6.2.2 Market support and energy policies

As seen in Figure 8, the Japanese market has stabilised at around 300 MW/year the last years, while the German market is increasing and might soon exceed 1 GW/year. Germany has a very favourable market support programme in form of a FIT, and it has been argued that the Japanese market is now self-sustained, and that this levelling off can be explained by lack of silicon.[18] There are also large differences in the existing institutions – the energy policies – which will now be further elaborated.

One of the benefits of the German FIT is that it provides economical incentives for end-use customers to buy PV systems, reducing the pay-back period to perhaps a few years. In this way, the market is greatly expanded from those who buy PV out of reasons of environmental consciousness to those interested in investment possibilities, thus also increasing ’legitimation’.

In Japan, the voluntary programme for net-metering and buy-back of excess electricity from PV induces the ’formation of markets’, and was very important for the formation of the grid-connected rooftop market. This market has been the most important one for PV in Japan during the last years (IEA-PVPS, 2006). The programme also influences the ’direction of search’, by specifying a main application for PV manufacturers to focus on. However, a difference between the net-metering system and the system in Germany is that it does not provide enough economic incentives to make a PV system economically viable; electricity generated from a typical household PV system is twice as expensive as that bought from the grid. Also, as it is a voluntary programme, it may not provide the same financial security as a law. Another available support system, the RPS system, does not seem to function to induce market formation either.

The combined power of the Japanese support measures do not provide financial incentives for buying a PV, hence people buy PV for “emotional” reasons.

The residential dissemination programme, though very successful for creating a market, was not connected to goals for actual PV diffusion, and even though a target was to create a self-sustained

[18] It is interesting to see that shortage of silicon may have facilitated the entrance of new companies aiming for non-c-Si technologies, such as Honda or Showa Shell. Thus, an increase in ’entrepreneurial experimentation’ and change in the ’direction of search’ can be observed.

market, it may have been terminated too early. To the best of our knowledge, the target price of the programme was not connected to knowledge of what was needed for people to buy PV (JPEA, 2008). Indeed, Kimura and Suzuki (2006) state that there was much uncertainty in METI before introducing this programme. It has been suggested that this government support may have been important in Japan as a sign to users that the government is supporting the technology, thus strongly affecting the process of legitimation' (Kimura and Suzuki, 2006; Kushiya, 2008). As described above, the level of subsidy was very low at the end, but may in line of this reasoning have been important symbolically. This lack of knowledge of how the demand is articulated by customers – why people buy PV, in this case – is also described by Bergek et al. (2008) as a process that hinders market formation.[19]

Summing up, further 'market formation' in Japan could be blocked by lack of financial incentives for end customers and little knowledge on the articulation of demand. Also, if 'legitimation' was enhanced by a small but symbolic governmental support, the withdrawal of the support could imply a blocking of this function.

6.2.3 The role of organisations for creating legitimacy and institutional change

The German institutional changes were initiated and carried through largely due to the existence and work of organisations, who could lobby at many different levels. They were able to gather a variety of different interest groups when lobbying for change, including utilities and unions. Also of importance was the existence of other renewable TIS, and the work of environmental NGOs such as Greenpeace. The pathway was such that the FIT was at first introduced at a local level in Aachen, and later on a national level.

We have not been able to see the same organisational development in Japan as in Germany. Corresponding Japanese organisations have appeared roughly with a 10 year time lag: GSEIA was founded in 1976 and JPEA in 1989; Eurosolar in 1988 and Japanese Diet Members Promoting Renewable Energies in 1999. The activity of environmental NGOs has not been observed during this study. Interestingly, two very important measures for PV in Japan seem to have been realised due to the initiatives of single persons (regulation changes and PV2030) and not organisations. The implications of this will be elaborated in Section 8 below.

The person behind the initiative for the "Federation of Diet Members for Promoting Natural Energy" is now working on introducing ideas and concepts first on a local level, for example through the Tokyo Metropolitan Office. Following the German example, activities at a local level may prove to be an important inducement mechanism for further diffusion, if they can progress from the local to the national level.

In summary, though Japanese interest groups have started to build legitimation on a local level – which proved successful in Germany – they seem to be less organised and influential politically. Adding the fact that environmental NGOs seem to be less active, we suggest that their absence constitute an important blocking mechanism for further 'legitimation' of PV.

6.2.4 Strong role of electrical utilities

A topic related to the previous section is the roles that the electrical utilities have played in each country. In Germany, it was for example possible to for the Green Party to get support from a utility when suggesting introduction of a feed-in tariff. In Japan, the ten large utilities are gathered in the Federation of Electrical Power Companies (FEPC), a lobby organisation "with huge

[19] Honda is one of the only large companies that focuses solely on the Japanese market today, stating that it is very important for them to get customer feedback (Matsuura, 2008).

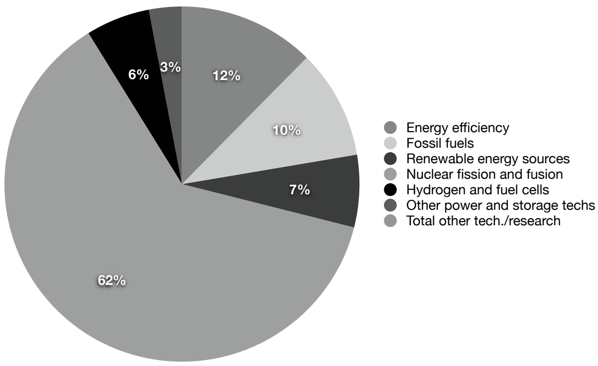

Figure 9: Energy R&D
Source: IEA (2008)

influence", making changes slow (Kimura and Suzuki, 2008). On the other hand, utilities in Japan voluntarily introduced net-metering, while German utilities refused to do something voluntarily, even though they were pressured to do so by the German Ministry of Finance.

The strong position of the utilities may have influenced the 'direction of search' of systems researchers to a larger extent in Japan than in Germany. An important part of the Ota City project is to investigate the phenomena of "islanding", as discussed above. An interviewee state that "Utilities are following strict regulations on frequency and voltage fluctuations, so that the quality of electricity is very different from Germany" (Kushiya, 2008).

This suggest that it may be interesting to investigate further whether the regulations on electrical stability functions as a blocking mechanism.

6.2.5 A stronger TIS can block diffusion

Another large difference between Germany and Japan is the existence of a larger energy TIS in the form of nuclear technology in Japan. While Germany decided to phase out nuclear after Chernobyl, Japan stayed on track.

Since 1951, an important theme has been to increase Japan's self sufficiency in energy, mostly by developing nuclear technology and creating a closed nuclear fuel cycle through breeder reactors (METI, 2006*b*). Still, the only goals for an energy source in the national energy policy is for nuclear – 30-40% "or more" by 2030 "or beyond" (METI, 2006*a*). There are no official goals for PV except as part of the RPS system. Also, the largest part of governmental R&D goes to nuclear, as seen in Figure 9.

What is noteworthy is that the two technologies are not really competing technologies in terms of market size. If the goals for PV2030 are realised, 10% of the national energy supply will be from PV, which does not seem to conflict with the goals for nuclear. As discussed above, the national targets for PV 2010 will be missed. Interviewees explained that the goals were decided so that no one was ultimately responsible, and that top-down goals are rare in Japan (Kimura and Suzuki, 2008). This may block further 'legitimation' of PV as a national energy source.

7 Key policy issues

From the blocking mechanisms that have been identified, five key policy issues emerges (see Figure 10):

- **Compliment nuclear targets with targets for different renewables**. To avoid the blocking effect of the powerful nuclear innovation system in Japan, measures should be taken to merge the two opposing views on the future energy system in Japan. METI could, for instance, include numerical targets for both nuclear energy and renewable energy in the same policy documents or law. In line of our previous argument about the importance of technology-specific policies, specific targets could be set for different technologies.
- **Support environmental NGOs**. The influence of NGOs in Germany has proved successful in promoting renewable energy, and could be so in Japan as well. An important measure would thus be to increase their role.
- **Investigate the need for very high grid stability**. In Japan, grid stability issues are much researched, and tested, such as in the Ota City and Rokko projects. A corresponding development has not been seen in the German development. As the high demands for grid stability block the diffusion of PV, we suggest an investigation if Japan has the need for a more high-stability grid than other places.
- **Ensure long-term financial incentive for customers**. This can be done by transforming the voluntary net-metering and buy-back programme into a law, or in some other way guarantee the long-term incomes from installing a PV system. A system that has proven successful in Germany is the feet-in tariff system. This could be one of the possible policy alternatives, and should be reconsidered after seeing its success elsewhere.
- **Reduce uncertainty about why people buy PV in Japan**. This can for instance be done through green market research, and put finally put to rest the question of why people buy PV in Japan, even though it is not a good investment, financially.

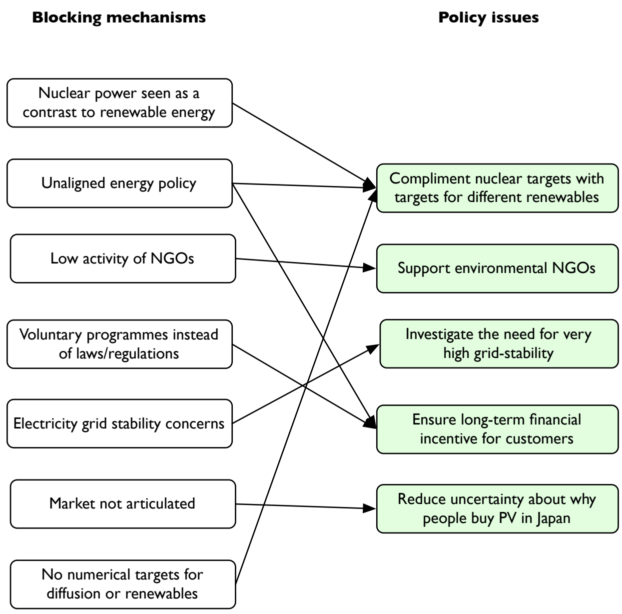

Figure 10: Blocking mechanisms and key policy issues for the Japanese PV innovation system.

8 Discussion and conclusions

The purpose of this study was to study the functional dynamics of the Japanese PV innovation system, in order to understand the diffusion of PV in Japan, and more specifically to identify blocking mechanisms, hindering the diffusion of the technology. Key policy issues, related to the blocking mechanisms were then pointed out. In total, seven blocking mechanisms for diffusion of PV in Japan were identified:

- Nuclear power is seen as a contrast to renewable energy
- Unaligned energy policy
- Low activity of NGOs
- Volontary programmes instead of laws/regulations
- Electricity grid stability concerns
- Market not articulated
- No numerical targets for diffusion of renewables

Some of these issues has been pointed out before. Kimura and Suzuki (2006) discusses potential problems of further diffusion due to the fact that net-metering is a voluntary programme, and thus its future uncertain, together with the fact that the governmental market support programmes has weakened. These are connected to the blocking mechanisms “unaligned energy policy”, “no numerical targets for diffusion of renewables” and “voluntary programmes instead of laws/regulations”. They also highlight the importance of niche markets when introducing a new technology, in this case people willing to pay for a PV system even though it is not economically 'rational'. This connects well with our conclusion that the market is not articulated; even though there was a market for initial growth, it was not enough for creating a self-sustained market.

The analysis by Gonnermann and Iida (2007) points to the German FIT being much superior to the Japanese RPS system, since the RPS system does not provide an incentive for further diffusion, favours the cheapest form of renewable energy, and does not have a severe penalty. It is also pointed out that there is no possibility for an investor in renewable energy to plan for the long-term in Japan. These conclusions are related to the “unaligned energy policy” and “no numerical targets for diffusion of renewables” blocking mechanisms that were found in this study.

Some of the other identified blocking mechanisms, such as “low activity of NGOs” and “electricity grid stability concerns” does not appear to have been identified in previous studies, and arose largely out of the comparison with Germany.

From the blocking mechanisms, a set of five policy issues were suggested:

- Compliment nuclear targets with targets for different renewables
- Support environmental NGOs
- Investigate the need for very high grid stability
- Ensure long-term financial incentive for customers
- Reduce uncertainty about why people buy PV in Japan

During our study, we have come upon a number of complexities, which will be elaborated below. We will also suggest some points of further research.

- **Short study**. This master's thesis was a project limited to 20 weeks, during which we stayed three months in Japan. Only two interviews were possible to arrange in January before going to Japan, which meant that much time was spent on practical issues such as making contact with new actors, and setting up meeting times. If additional actors and actor groups could have been interviewed, the analysis could have been made more complete.
- **Validity of the analytical framework in a Japanese context**. As discussed above, we have seen that the actions of individual people may have played a large importance for Japanese PV, whereas emphasis in previous TIS studies have been put on the role of organisations. Therefor, the Japanese situation has been interpreted as lacking actors that create 'legitimation'. The framework is developed empirically from case studies of Western countries, which leads to the question whether there are aspects of the framework that rule out important aspects of Japanese PV innovation processes. In the context of this example, the best way to create 'legitimation' for a technology in Japan, may not be what is required in Germany. It would be an interesting topic for further study whether the framework needs to be complemented in some way to fully take into account Japanese-specific differences.
- **Choice of reference system guiding our direction of search**. In the analysis by Jacobsson et al. (2004) and Jacobsson and Lauber (2006), great emphasis is put on the role of organizations for creating 'legitimation'. This, of course, lead us in the search in finding corresponding success factors in Japan. Other aspects may well have played important roles. Comparisons with other countries may lead to new interesting conclusions, and it is thus something we suggest for further research.
- **Few exisisting studies of other energy TIS**. Jacobsson et al. (2004) and Jacobsson and Lauber (2006) show that other strong renewable TIS in the form of wind and hydro aided the growth of solar. As discussed above, nuclear is included in Japanese national energy strategies to a much further extent than solar, whereas German nuclear is to be phased-out. An increased knowledge of these other systems in Japan would in this way increase the understanding of the PV innovation system, and would thus be a good topic for furter research.
- **No access to potentially interesting sources**. Due to the language barrier, many Japanese articles and reports were not accessible for references. Besides references in Japan, two important sources in English were not available – "PV News", published by the Prometheus Institute, and the "PV Market in Japan" report, published by RTS Corporation, due to the high cost of access. A tracking of trends through these sources would possibly add new interesting points to the analysis.

Overall, the framework that we used was effective as a means of gathering and sorting information. It was well suited even for a short study like ours, especially since the paper of Bergek et al. (2008) was written as a guide – "a practical scheme of analysis for policy makers". Though the intended audience is a policy maker, the analysis should of interest to anyone in the field of renewable energy. It is perhaps not obvious, for example, that different proponents of renewable technologies could benefit from acting together politically, even though they are competing on the same market as the case was in Germany.

We hope that this thesis may be used as inspiration for a continued research on the diffusion of renewables, both in Japan and elsewhere. Increasing the amount of renewables and transforming energy systems are urgent matters.

References

Abe, S. (2007), 'Invitation to 'Cool Earth 50 – 3 proposals, 3 principles'. Speech by the Prime minister of Japan given on 24 May 2007. Transcript available at http://www.kantei.go.jp/foreign/abespeech/2007/05/24speech_e.html. Accessed 10 June 2008.

ANRE (2006), 'Energy in Japan 2006 – Status and Policies'. Agency for Natural Resources and Energy, Ministry for Economy, Trade and Industry, Tokyo, Japan.

Bahaj, A. S. (2002), 'Means of enhancing and promoting the use of solar energy', *Renewable Energy* **27**(1), pp. 97–105.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S. and Rickne, A. (2008), 'Analyzing the functional dynamics of technological innovation systems: A scheme of analysis', *Research Policy* **37**, pp. 407–429.

Carlsson, B. and Stankiewicz, R. (1991), 'On the nature, function and composition of technological systems', *Journal of Evolutionary Economics* **1**(2), pp. 93–118.

Crassard, F. and Rode, J. (2007), The evolution of building integrated photovoltaics (BIPV) in the German and French technological innovation systems for solar cells, Master's thesis, Division of Environmental Systems Analysis, Chalmers University of Technology, Gothenburg, Sweden. ESA Report No 2007:16.

Dooley, J. (1999), 'Energy R&D in Japan', *Prepared for the US Department of Energy, Contract DEAC06-76RLO* .

Gonnermann, T. and Iida, T. (2007), The political framework for renewable energies in Japan and Germany – A comparative analysis for wind power and photovoltaic. Institute for Sustainable Energy Policies, Tokyo, Japan.

Hamakawa, Y. (1994), 'Recent advancements in amorphous silicon solar cells and its new role for environmental issue', *Renewable Energy* **5**, pp. 33 – 43.

Hashimoto, I. (2003), 'Present status of research and development of PV technology in Japan', *Proceedings of 3rd World Conference on Photovoltaic Energy Conversion* **3**, pp. 2522–2526.

Hekkert, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S. and Smits, R. (2007), 'Functions of innovation systems: A new approach for analysing technological change', *Technological Forecasting & Social Change* **74**(4), pp. 413–432.

Hoogwijk, M. M. (2004), On the global and regional potential of renewable energy sources, PhD thesis, Science Technology and Society. Utrecht University, Utrecht.

IEA (2005), 'Share of total primary energy supply in 2005'. International Energy Agency. Available at http://www.iea.org/textbase/stats/pdf_graphs/JPTPESPI.pdf. Accessed 12 June 2008.

IEA (2008), 'IEA R&D Statistics Database'. International Energy Agency. Available at http://wds.iea.org/. Accessed 21 April 2008.

IEA-PVPS (2000), 'Trends in photovoltaic applications in Selected IEA countries between 1992 and 1999'. IEA Photovoltaics Power Systems Programme, Report T1-08:2000.

IEA-PVPS (2003), 'Trends in photovoltaic applications: Survey report of selected IEA countries between 1992 and 2002'. IEA Photovoltaics Power Systems Programme, Report T1-12:2003.

IEA-PVPS (2006), 'Trends in photovoltaic applications: Survey report of selected IEA countries between 1992 and 2005'. IEA Photovoltaics Power Systems Programme, Report T1-15:2006.

IEA-PVPS (2007), 'Trends in photovoltaic applications: Survey report of selected IEA countries between 1992 and 2006'. IEA Photovoltaics Power Systems Programme, Report T1-16:2007.

Imoto, J. and Ishimura, M. (2008), 'Personal communication with Junpei Imoto, NEDO and Masanori Ishimura, PVTEC'. 5 March 2008, Kawasaki, Japan.

IPCC (2007), 'Climate Change 2007: Synthesis Report – An assessment of the Intergovernmental Panel on Climate Change'. Valencia, Spain.

Jacobsson, S. and Bergek, A. (2004), 'Transforming an energy system: the evolution of technological systems in renewable energy technology', *Industrial and Corporate Change* **13**(5), pp. 815–849.

Jacobsson, S. and Johnson, A. (2000), 'The diffusion renewable energy technology: an analytical framework and key issues for research', *Energy Policy* **28**(9), pp. 625–640.

Jacobsson, S. and Lauber, V. (2006), 'The politics and policy of energy system transformation – explaining the German diffusion of renewable energy technology', *Energy Policy* **34**(3), pp. 256–276.

Jacobsson, S., Sandén, B. A. and Bångens, L. (2004), 'Transforming the energy system – the evolution of the German technological system for solar cells', *Technology Analysis and Strategic Management* **16**(1), pp. 3–30.

JPEA (2008), 'Personal communication with Junichi Honda, Kyocera; Tetsuzo Kobayashi, Eko Instruments Corporation; Masahiro Sakurai, Fuji Electric Systems and Takayuki Nakajima, JPEA'. 17 April 2008, Tokyo, Japan.

Jäger-Waldau, A. (2007), PV Status Report 2007 – Research, Solar Cell Production and Market Implementation of Photovoltaics, Technical report, European Commission, DG Joint Research Centre, Institute for Environment and Sustainability.

Kaizuka, I. (2008), Current Status and Prospects of Photovoltaics in Japan, *in* '4th Workshop on the Future Direction of Photovoltaics – Proceedings', Japan Society for Promotion of Science.

Kimura, O. and Suzuki, T. (2006), '30 years of solar energy development in Japan: co-evolution of technology, policies, and the market', Paper prepared for the 2006 Berlin Conference on the Human Dimensions of Global environmental change: Resource policies: Effectiveness, Efficiency and Equity.

Kimura, O. and Suzuki, T. (2008), 'Personal communication with Osamu Kimura and Tatsujiro Suzuki, Socio-economic Research Center, Central Research Institute for Electric Power Industry'. 10 March 2008, Tokyo, Japan.

Kitamura, A., Okamoto, M., Hotta, K., Takigawa, K., Kobayashi, H. and Ariga, Y. (1993), 'Islanding prevention measures: demonstration testing at Rokko Test Center for Advanced Energy Systems', *Photovoltaic Specialists Conference, 1993., Conference Record of the Twenty Third IEEE* pp. 1063–1067.

Kurokawa, K. (1994), 'Japanese activities for introducing residential PV systems as a national energy supply', Paper prepared for the 1st World Conference on Photovoltaic Energy Conversion, 5–9 December 1994, Hawaii.

Kurokawa, K. (2008), 'Personal communication with Professor Kusoke Kurokawa, Tokyo University of Agriculture and Technology'. 7 April 2008, Tokyo, Japan.

Kurokawa, K. and Ikki, O. (2001), 'The Japanese experiences with national PV system programmes', *Solar Energy* **70**(6), pp. 457–466.

Kushiya, K. (2008), 'Personal communication with Dr. Katsumi Kushiya, CIS Development Group, Showa Shell Sekiyu'. 6 February, Kashiwa and 22 April 2008, Atsugi, Japan.

Markard, J. and Truffer, B. (2008), 'Technological innovation systems and the multi-level perspective: Towards an integrated framework', *Research Policy* **37**(4), pp. 596–615.

Matsuura, Y. (2008), 'Personal communication with Yasuko Matsuura, Corporate Communication Division, Honda'. 9 April 2008, Tokyo, Japan.

METI (2006*a*), 'New National Energy Strategy – Digest'. Ministry for Economy, Trade and Industry, Japan. Available a http://www.enecho.meti.go.jp/english/report/. Accessed 6 May 2008.

METI (2006*b*), 'The Challenges and Directions for Nuclear Energy Policy in Japan: Japan's Nuclear Energy National Plan'. Nuclear Energy Policy Planning Division, Ministry for Economy, Trade and Industry, Japan. Available at http://www.enecho.meti.go.jp/english/report/. Accessed 12 June 2008.

Nagamatsu, A., Watanabe, C. and Shum, L. K. (2006), 'Diffusion trajectory of self-propagating innovations interacting with institutions –incorporation of multi-factors learning function to model PV diffusion in Japan', *Energy Policy* **34**, pp. 411–426.

NEDO (2004), 'Overview of PV Roadmap Toward 2030 (PV2030)'. New Energy and Industrial Technology Development Organization, Kanagawa, Japan.

NEDO (2007), 'Environment & Energy Booklet 2007'. New Energy and Industrial Technology Development Organization, Kanagawa, Japan.

Niki, S. (2008), 'Personal communication with Dr. Shigeru Niki, TeamLeader: Thin Film Compound Semiconductor Team, AIST'. 18 March 2008, Tsukuba, Japan.

Nishikawa, S. (2008), 'Personal communication with Dr. Shogo Nishikawa, Nihon University.'. 18 March 2008, Tokyo, Japan.

OECD (2007), 'OECD Annual Statistical Bulletin, 2006'. Organisation for Economic Co-operation and Development, pp. 117, Vienna, Austria.

Ozaki, M. (2008), 'Personal communication with Masayoshi Ozaki, Corporate Solar Energy Group, Kycoera'. 11 April 2008, Kyoto, Japan.

Palmblad, L., Jacobsson, S., Sandén, B. and Hall, M. (2007), 'Dynamics of the Swedish PV innovation system – the impact of a recent market formation program'. RIDE/IMIT Working Paper No. 84426–012. Available at http://www.imit.se/reports/.

Porsö, J. (2008), The effects of a Swedish investment support for photovoltaics on public buildings – An analysis of the dynamics of the innovation system, Master's thesis, Division of Environmental Systems Analysis, Chalmers University of Technology, Gothenburg, Sweden. ESA Report No 2008:8.

RPS (2008), 'Outline of the RPS system in Japan'. Available at http://www.rps.go.jp/RPS/new-contents/english/outline.html. Accessed 20 May 2008.

Saitoh, T. (2003), '30 years of progress in crystalline silicon solar cells', *Proceedings of 3rd World Conference on Photovoltaic Energy Conversion, 2003* **1**, pp. 23–28.

Sandén, B. (2005), 'The economic and institutional rationale of PV subsidies', *Solar Energy* **78**, pp. 137–146.

Sanyo (2007), 'Think Gaia – Sanyo Electric Co. Ltd Sustainability Report 2007'. Available at http://www.sanyo.co.jp/environment/en/pdf/index.html. Accessed 8 June 2008.

Shino, K. and Ikki, O. (2003), 'National Survey Report of PV Power Applications in Japan 2002'. Report prepared under Task 1 of the International Energy Agency Photovoltaic Power Systems Programme.

Smil, V. (2003), *Energy at the Crossroads – Global Perspectives and Uncertanties*, MIT Press, Cambridge, Massachusetts, London, England.

Tsujimura, K. and Matsushita, T. (2008), 'Personal communication with Katsushi Tsujimura and Teruji Matsushita, Global Sales & Marketing Department, Sharp Solar Systems Group'. 27 February 2008, Katsuragi, Japan.

Watanabe, C., Wakabayashi, K. and Miyazawa, T. (2000), 'Industrial dynamism and the creation of a 'virtuous cycle' between R&D, market growth and price reduction The case of photovoltaic power generation (PV) development in Japan', *Technovation* **20**(6), pp. 299–312.

WEC (2007), '2007 Survey of Energy Resources, World Energy Council'.

Yamamoto, K. (2008), 'Personal communication with Kenji Yamamoto, Frontier Materials Development Laboratories, Corporate R&D Division, Kaneka Corporation'. 11 April 2008, Settsu, Japan.

A Interviews and events

Table 1 lists the interviews that were performed in Japan to gather data for this study. All interviews were face-to-face unless otherwise stated. Table 2 lists the events that were attended during the study in order to find contacts, improve the understanding of PV and the current situation of the technology in Japan.

Person(s)	Position	Company/Organisation
Katsumi Kushiya	Deputy General Manager, CIS Development Group Chief Researcher, New Business Development Division Visiting Professor, Integrated Research System for Sustainability Science	Showa Shell Sekiyu K.K. University of Tokyo
Satoshi Hoshino	CEO, IM Training Institute	JANBO
Yoshimi Kajikawa	Deputy Secretary General	JANBO
Yasunori Baba	Professor, RCAST	University of Tokyo
Katsushi Tsujimura	Assistant manager, Global Sales & Marketing Department II	Sharp Solar Systems Group
Teruji Matsushita	Global Sales & Marketing Department II	Sharp Solar Systems Group
Junpei Imoto	Project Coordinator, New Energy Technology Development Department	NEDO
Masanori Ishimura	Chief Researcher, Technical Department	PVTEC
Osamu Kimura	Research Economist, Socio-economic Research Center	CRIEPI
Tatsujiro Suzuki	Associate Vice President, Socio-economic Research Center Visiting professor, Graduate School of Public Policy	CRIEPI University of Tokyo
Shogo Nishikawa	Associate Professor, Department of Electrical Engineering	Nihon University
Jiro Ohno	Deputy General Manager, Architectural Design Division	Nihon Sekkei
Bjørn Sandberg	General Manager	Q-Cells Japan
Tetsunari Iida	Executive Director	Institute for Sustainable Energy Policies
Kosuke Kurokawa	Professor, Strategic Research Initiative for Sustainability & Survival Graduate School General Chairperson	Tokyo University of Agriculture & Technology Japan Council for Renewable Energy
Yasuko Matsuura	Assistant Manager, Corporate Communication Division	Honda Motor Corporation
Shigeru Niki	Deputy Director, TeamLeader: Thin Film Compound Semiconductor Team	AIST

Table continues on the next page

Person(s)	**Position**	**Company/Organisation**
Koichi Sakuta	Principal Research Scientist, Research Center for Photovoltaics	AIST
Masayoshi Ozaki	Manager, Marketing Section, Corporate Solar Energy Group	Kyocera Corporation
Kenji Yamamoto	Senior Manager, Frontier Materials Development Laboratories, Corporate R&D Division	Kaneka Corporation
Fumiyasu Sezaki	Assistant Manager, Frontier Materials Development Laboratories, Corporate R&D Division	Kaneka Corporation
Takashi Ohigashi	Manager, Investigation Division	RTS Corporation
Izumi Kaizuka	Manager, Overseas Division	RTS Corporation
Takayuki Nakajima	General Manager, International Department	JPEA
Tetsuzo Kobayashi	General Manager, Production Engineering Department, Meteorology, Environment and New Energy Division	Eko Instruments Corp. (JPEA)
Junichi Honda	Manager Sakura Solar Center, Corporate Solar Energy Group	Kyocera Corporation (JPEA)
Masahiro Sakurai	Staff General Manager – Project Promotion, Energy Systems Department, Energy Solutions Division, Automation & Solutions Business Group	Fuji Electric Systems (JPEA)
Mr. Ishikawa	Director of the Division of Facilities Management of the Kashiwa Campus	University of Tokyo

Table 1: A list of interviews performed in Japan for the study.

Event	**Dates**	**Organiser**
PVExpo & Technical Conference 2008	27–29 February 2008	Reed exhibitions Japan Ltd.
4th Workshop on the future direction of PV	6–7 March 2008	JSPS
GIES 2008, Symposium	13 March 2008	GIES Organizing Committee
Seminar on PV in Wales	25 February 2008	NISTEP
Sweden – Japan Symposium on Sustainable Urban Development	17 April 2008	Embassy of Sweden in Japan, Ministry of Environment of Japan and United Nations University

Table 2: A list of events that were attended during the study.

B Abbreviations

AIST	National Institute of Advanced Industrial Science and Technology (2001–)
	Agency of Industrial Science and Technology (1948–2001)
ANRE	Agency of Natural Resources and Energy
a-Si	Amorphous silicon
BIPV	Building-integrated photovoltaics
BOS	Balance Of System
CO_2	Carbon dioxide
CRIEPI	Central Research Institute of Electrical Power Industry
c-Si	Crystalline silicon
DGS	Deutschen Gesellschaft für Sonnenenergie (German Society for Solar Energy)
FEPC	Federation of Electric Power Companies
FIT	Feed-In Tariff
GIES	Global Innovation Ecosystem
GSEIA	German Solar Energy Industries Association
IEA	International Energy Agency
IPCC	Intergovernmental Panel of Climate Change
JANBO	Japan Association of New Business Incubation Organizations
JPEA	Japan Photovoltaic Energy Association
JSEC	Japan Solar Energy Corporation
JSPS	Japan Society for the Promotion of Science
LNG	Liquefied Natural Gas
METI	Ministry of Economy, Trade and Industry
MITI	Ministry for International Trade and Industry
NEDO	New Energy and Industrial Technology Development Organization (1988–)
	New Energy Development Organization (1980–1988)
NGO	Non-Governmental Organisation
NISTEP	National Institute of Science and Technology Policy
OECD	Organisation for Economic Co-operation and Development
PV	Photovoltaics
PVTEC	Photovoltaic Power Generation Technology Research Association
R&D	Research and Development
RCAST	Research Center for Advanced Science and Technology
RPS	Renewable Portfolio Standard
SPD	Sozialdemokratiskche Partei Deuchlands (German Social Democratic Party)
TIS	Technological Innovation System

Table 3: A list of abbreviations used throughout this paper.