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30 years of solar energy development in Japan: co-evolution process of technology, policies, and the market

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Abstract
Technology development for a low-carbon economy, such as renewable energy development, plays a vital role in the global climate strategy. This article analyses the 30 years history of solar energy development in Japan, and explores the reasons for the successful diffusion of solar cells from the mid 1990's. It reveals that a major success factor has been the combination of a consistent technology-push policy, the Sunshine Program established just after the Oil Crisis, and demand-pull polices, such as net-metering system and investment subsidies from the early 1990's. It also analyses the policy process as to how these policies were formulated out of the struggle among the government, producers, and utilities, and how such policy instruments influenced technological innovations by stable R&D support, procurement, and removing regulatory barriers. The analysis also points out the response by high-income consumers, the dominant purchasers of solar cells in Japan, as another critical factor. Finally, the article asserts that, although Japanese photovoltaic development and diffusion seem to be an 'early success', its future development is highly uncertain due to the ongoing deregulation of utilities and the weak diffusion support by the government.

1. Introduction

Technology development for a low-carbon economy plays a vital role in the global climate strategy. Various energy scenario analyses show that the world society has to reduce its greenhouse gas emission by more than 80 % from the 1990 emission level by the end of this century in order to by then stabilize greenhouse gas concentration in the atmosphere at a low enough level to avoid serious economic and social impacts (IPCC, 2000, 2001). This requires a radical shift from the conventional energy system to a zero-carbon system, which consists of non-carbon emitting energy sources and highly efficient technologies in the

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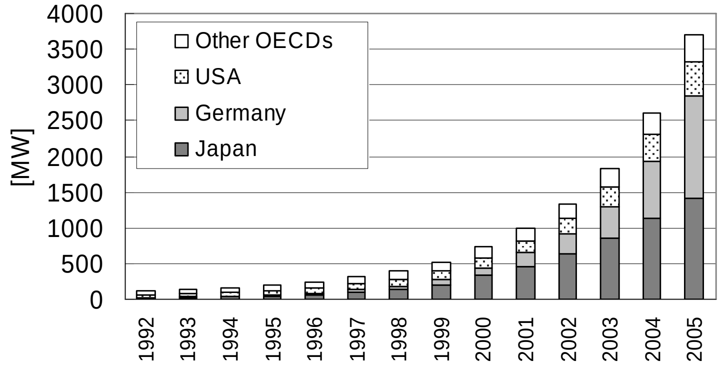

Figure 1 Cumulative PV installation in OECD countries, 1992-2005. *Source: IEA-PVPS (2006)*

energy conversion and end-use sectors.

A shift from a dominant technology to a next generation takes quite a long time, often decades in the case of energy technologies (Grübler & Nakicenovic, 1997), and involves complex interactions including technical as well as social and institutional factors. While there is a growing body of literatures on the macro-level dynamics of long term technological change (e.g. Grübler, 1998), the micro-level mechanisms as to how technological changes come about (e.g. Geels, 2005), and the role that the government can play in the innovation processes (Åhman, 2006; Margolis, 2002; Norberg-Bohm, 2000, 2002), there is much left to be analysed in order to have empirical foundations that can guide effective policy-making for energy technology innovation.

The aim of this paper is to contribute to this policy challenge by examining the history of the photovoltaic solar cells (PV) development in Japan. Since the Oil Crises in the 1970's, the Japanese government and firms have been taking great effort to research and develop PV in order to develop alternative energy to fossil fuels and to mitigate climate change. Now Japanese firms are capturing almost 50 percent share of the global PV market (RTS Corp., 2006), and the installed capacity in Japan is also leading the world (Figure 1). While Japanese PV development is often cited as one of the successful cases of energy technology innovation (see e.g. IEA, 2003, Bolinger *et al*., 2002), there have been few empirical analyses on the experience[1]. The major contribution of this paper is to provide the first in depth description of the 30 years history of PV development in Japan.

Based on a socio-technical systems perspective (Åstrand & Neij, 2006; van den Ende & Kemp, 1999; Rip & Kemp, 1998; Carlsson & Stankiewicz, 1991), we describe the history as a co-evolution process in which an infant technology in a basic R&D stage was

[1] Notable exceptions are Watanabe (1999), Watanabe *et al.* (2000) and Nagamatsu *et al.* (2006), which provide quantitative analyses on the relationship between R&D investment, production, and price reduction (all in English), and Shimamoto (1998), which provides detailed historical accounts from 1973 to the early 1990's (in Japanese).

dramatically improved both technologically and economically over decades, entered the market as a practical power-generation technology, and its industry has grown in recent years to more than US$ 3 billion in annual sales, in tandem with social and institutional changes, such as emergence of climate change issue and establishment of various support policies. Although the technology has a long way to go before being competitive with incumbent fossil-fuel based technologies, the experience so far should have important lessons on future energy technology policies.

This paper is organized as follows. In Section 2, we provide a brief introduction of the Japanese energy system and an overview of the history of PV development in Japan. Section 3 describes the historical process as to how PV technology, support policies and the market co-evolved from the 1970's to the present. Section 4 analyses the key factors of the successful PV development in Japan. Finally, Section 5 provides conclusion and policy implications.

2. Background and overview

Due to the lack of domestic resources and the growth of energy demand, Japan has been heavily relying on imported primary energy sources. Oil Crises in the 1970's had a tremendous impact on the economy which was highly dependent on oil from the Middle East (more than 70% of the primary energy in the early 1970's). This made energy security one of the top issues of the nation, and the government began increasing energy supply from gas, coal and nuclear, as well as increasing energy efficiency and investing in "new energy" development, such as solar and geothermal energy. Although the low oil prices in the 1980's decreased the level of public attention on energy development and conservation, emergence of the climate change issue required the government to work even more on developing clean and efficient energy technologies. Among them solar energy technology, especially PV, has been a most prospective option that can provide substantial amount of clean energy in the future.

PV development in Japan was started just after the Bell Institute invented silicon solar cells in 1953. Some laboratories and private firms started R&D on photovoltaic solar cells. These early efforts resulted in a small number of commercial applications, such as spacecrafts, telecommunication stations in isolated places, and off-grid lighthouses in the 1960's and 70's. Figure 2 shows the trend of solar cells production in Japan from 1976 to 2005, from which we can distinguish three phases in its history:

1st Phase (1974-1984): In response to the first Oil Crisis, the government launched the *Sunshine Program*, a national R&D program aiming at providing substantial amount of new non-fossil fuel energy by 2000. This ambitious program formed the backbone of both public and private activities to develop new energy technologies. One of the major focuses

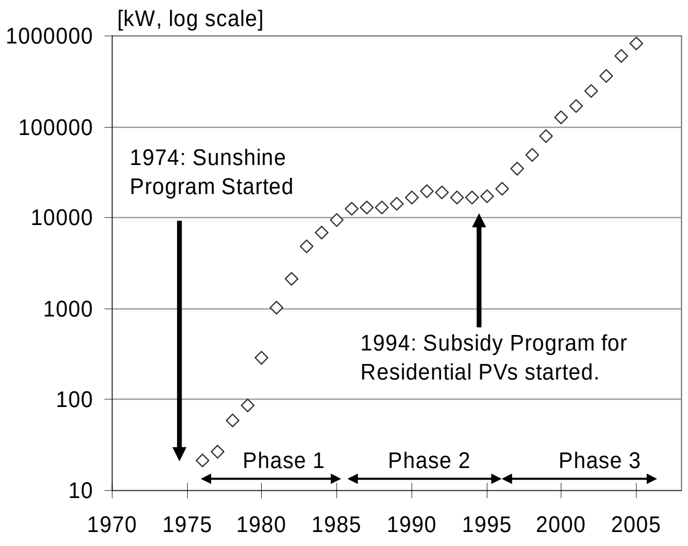

Figure 2 Trend of solar cells production in Japan, 1976-2005.

Source: IEEJ (1985) and RTS Corp. (2006).

was solar energy, and its budget was steeply raised after the second Oil Crisis in 1979.

Second Phase (1984-1994): Substantial progress had been made in the Sunshine Program. Many demonstration projects were also implemented. One producer, Sanyo, succeeded in commercialization of amorphous silicon (a-Si) PV in handy calculators, followed by other producers. The market was very small due to the lack of demand for power applications (Figure 2).

Third Phase (1994-): Since 1994, installations of residential PV systems has been rapidly increasing. The major stimulus were governmental interventions, such as simplified procedures of PV installation, technical guidelines for grid-connection, the investment subsidy for residential PV systems, and the net-metering system[2] provided by electric power companies. So far 94% of the PV installed in Japan is grid-connected residential PV systems with governmental subsidies (RTS Corp., 2006).

3. Co-evolution process of PV technology, support policies and the market

3.1. Formulation and expansion of the Sunshine Program (1974-1981) [3]

In order to understand the unique characteristics of the Sunshine Program, we take a look at how the program was formulated and expanded in response to the Oil Crises. The

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[2] "Net metering programs serve as an important incentive for consumer investment in renewable energy generation. Net metering enables customers to use their own generation to offset their consumption over a billing period by allowing their electric meters to turn backwards when they generate electricity in excess of their demand. This offset means that customers receive retail prices for the excess electricity they generate." (excerpted from US-DOE website: www.eere.energy.gov/greenpower/markets/netmetering.shtml, visited on September 2005)

[3] This section is based on Shimamoto (1998).

origin of the Sunshine Program was a research proposal on a solar energy technology by the National Electrotechnical Laboratory[4]. The proposal was submitted just a year before the first Oil Crisis as a new project in another national R&D program (the Large-scale Industrial Technology Program, which is called *Big Projects*), which was being conducted by the Ministry of International Trade and Industry (MITI) since 1966. As the oil dependence of the Japanese energy supply was already quite high at that time, MITI was very interested in the proposal to develop solar energy. But as it was clear that it would take quite a long time, from 20 to 30 years at least, for such new infant technology to be in practical use, the proposal was not acceptable as a subject of the Big Projects, which could fund only for 10 years at the longest. So MITI tried to start a different R&D program with a much longer-term perspective. While the idea was being debated inside MITI, other three energy technologies, namely coal liquefaction, geothermal, and hydrogen, were added and the budget request grew considerably from JPY 500 million to JPY 10 billion[5]. It was considered that "*the bigger the request, the easier to appropriate it will be, because if it gains political prominence it can get backing of politicians*"[6]. The first Oil Crisis was brought about just in the middle of the appropriation process, and it stimulated strong political and public support for establishing the program. It was believed to bring solution to the energy crisis. The program was established in 1974 with the budget of JPY 2.5 billion[7]. At the beginning, solar thermal generation was the top priority, and PV was a minor subject in the program.

The second Oil Crisis in 1979 urged the government even more to invest in alternative energy development, so the target and funding for the Sunshine Program was intensified. The original target to supply 1.6% of the total energy demand in 1990 was raised up to 5% in 1990 and 7% in 1995. In addition, "*Alternative Energy Act*" was enacted in 1980, which established the basic structure of alternative energy development policies as follows:

- *Electricity Tax* was raised to secure sufficient revenue for the policies;
- *Special Account for Alternative Energy Development* was established in the governmental fiscal system. This comes from the revenue of the electricity tax and the tax on coal use, and *exclusively* dedicates for alternative energy development; and
- *New Energy Development Organization (NEDO)*, a quasi-governmental organization, was established as the central actor responsible for new energy development.

The establishment of *the Special Account* was particularly important, because most of the budget of the Sunshine Program came from this Account (Figure 3a). As this *Special Account* is based on the tax revenues on electricity and coal, it became a stable and

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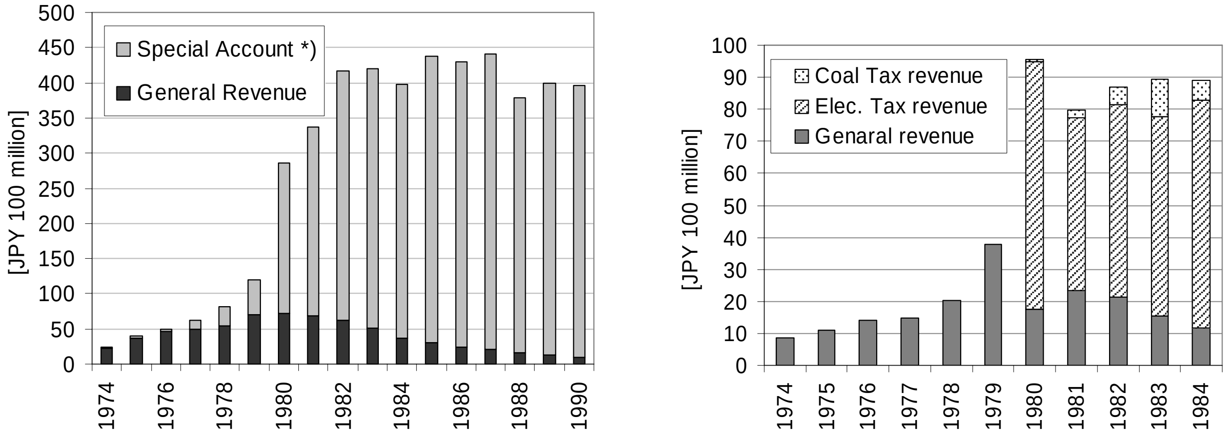
[4] Currently merged into the National Institute of Advanced Industrial Science and Technology (AIST).
[5] Approximately USD 4 million and 100 million, respectively (in the exchange rate of 120JPY/USD).
[6] Interview with a former Official of MITI, conducted by Shimamoto (1998).
[7] Approximately USD 20 million, based on exchange rate of 120JPY/USD.



a) Budgets of the Sunshine Program **b) Budgets of the PV development**

*) Special Account includes revenues from the coal use tax and the electricity tax.

Figure 3 Budgets by revenue sources of the Sunshine Program, 1974-1994.

(Source: MITI, 1984; Horigome, 1999)

sufficient source of R&D subsidies. As for the PV budget, a large part of it comes from the revenue of the electricity tax (Figure 3b).

The center pillar of the Sunshine Program was solar energy. Especially the solar thermal power generation was the core project in the 1970's. It was because the basic technologies of solar thermal power generation were already developed in other countries such as US and Spain and demonstrated good performance, whereas PV was too expensive in the early 1970's and believed to take many years before coming to the market. Two demonstration plants of 1 MW solar thermal power generation were constructed in the late 1970's, which were the world largest at that time. However, their performance was disappointing due to the characteristic of sunlight in Japan which turned out to be not suited for the generation. So MITI decided to terminate the solar thermal project in spite of the original plan to introduce an even larger plant (10MW) in the next ten years. In short, solar thermal power generation had failed. Then, the focus was shifted from solar thermal to PV. Accordingly the PV budget in 1981 was suddenly expanded, absorbing most part of the solar thermal budget of previous year (Figure 4). One of the reasons of this quick shift of budget was that MITI did not want the budget for solar power shrink. Officials in the solar energy division at MITI did not want to cut down their budget even though they had to terminate solar thermal power generation, and PV was a good alternative to succeed the budget (Horigome, 2003). In this way, PV gained large and stable budgets, not only on the basis of technical potential and expectations, but also by the failure of other technology and the governmental inertia in budget allocation.

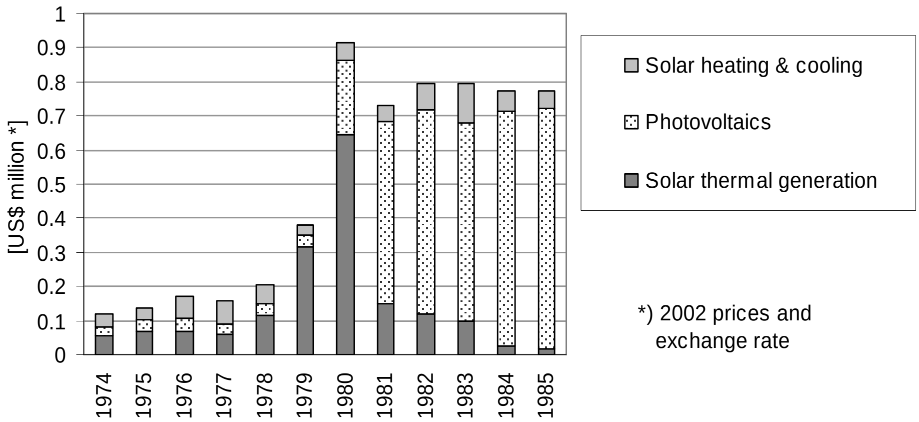


Figure 4 Budgets for solar energy technologies, 1974-1985. *(Source: IEA, 2004)*

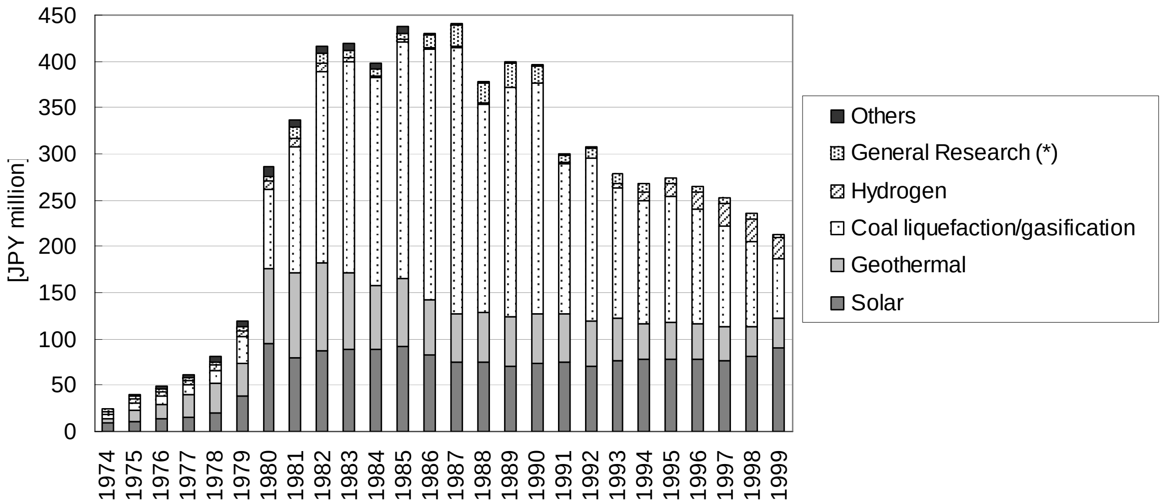


Figure 5 Budgets of the Sunshine Program, 1974-1999. *(Source: Horigome, 1999)*

3.2. Progress under the Sunshine Program (1981-1990)

One important result of the expansion of the Sunshine Program was the abundant, stable budget for PV development. Figure 5 shows that the level of PV budget keeps around the level of USD 6 billion during the 1980's and 90's, thanks to the *Special Account* as a protected source of funding. This provided a desirable R&D environment for researchers in the national laboratories because "*they did not have to worry about financial problems and could pursue their mission with abundant budget, which seems to be an important background of Japan having the top level in PV technology*" (Horigome, 2003).

PV development under the Sunshine Program was firstly joined by major appliance producers, including Sharp, Matsushita, Hitachi, Toshiba, and NEC (Nippon Electronics Company). It was later joined by Kyocera, Sanyo and more others. While most of these firms had conducted in-house R&D of PV more or less in the 1960's, the establishment of

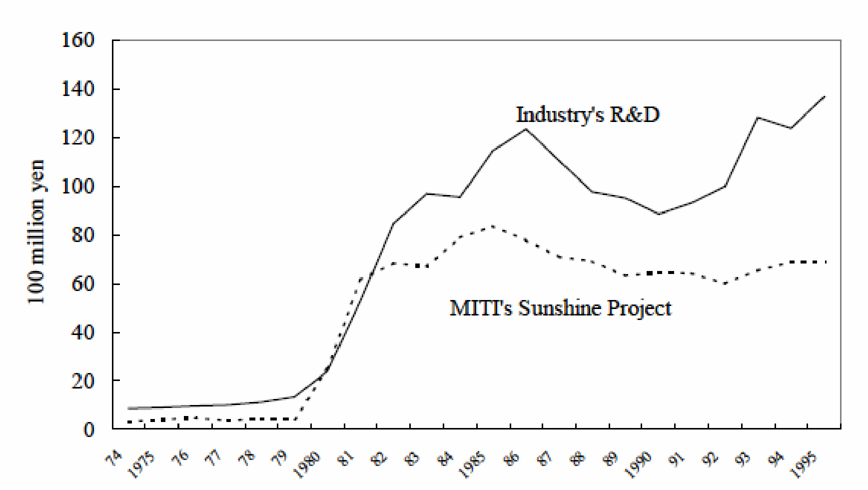


Figure 6 Trends in R&D Expenditure for PV R&D in Japan. *(adopted from Watanabe, 1999)*

the Sunshine Program was the biggest stimulus for these firms to expand their activities of PV development. What was important for private firms was not only the governmental R&D subsidies, but also the national target and commitment to introduce substantial amount of solar power by 2000, which meant a large future market of PV products. This stimulated several appliance producers to invest in PV technology in spite of the small subsidies that individual firms could receive from the government. As the government had a clear intention to develop and adopt PV, firms could have an expectation that there might be a large market of the technology in the future (Suzuki, 2004). This inducement mechanism is supported by Watanabe (1999)'s analysis, which shows that the strong commitment by the government to introduce PV very much stimulated private investments, which rose well over governmental subsidies (Figure 6).

The Program promoted not only basic R&D but also a number of demonstration projects, including distributed small applications as well as a large scale solar generation plant (1 MW plant in Saijo City). These demonstrations created an indispensable demand of solar cells. While the major objective of the demonstrations was system development, the NEDO demonstrations provided PV producers the *only* market in the 1980's, where producers could accumulate production experience and improve process technologies through learning-by-doing (PVTEC, 1998). NEDO set annual targets of cost reduction, and put pressure on producers, indicating that NEDO would not buy solar cells unless the price target was not achieved. As the NEDO procurement was the only market, the cost reduction target by NEDO was a strong incentive for firms to reduce production cost (Takeda, 2004). Thus, the NEDO demonstration projects had strong buy-down effect.

The result was the steady improvement of conversion efficiency and economics of PV in the 1980's (Figure 7 and Figure 8). When the Program was started, the efficiency (ratio of energy converted from sunlight) of solar cells produced in factories was only 5%,

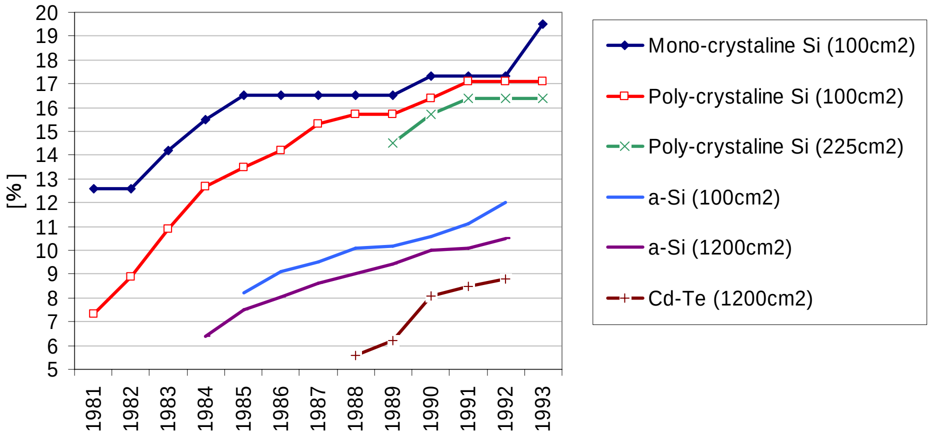


Figure 7 Trend of solar cell efficiency, 1981-1993. *(Source: Sharp 1996; PVTEC 1998)*

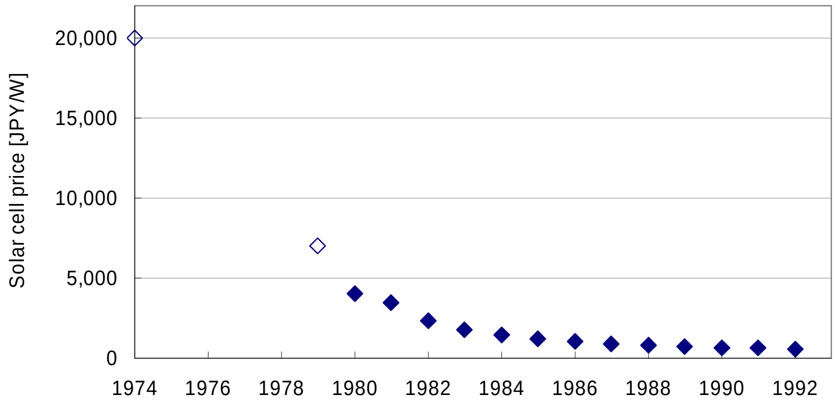


Figure 8 Cost reduction of solar cells from 1974 to 1992. *(Source: Mizutani, 1994)*

although champion data in laboratory already had 17% efficiency. It is said that having a stable production of high-quality solar cells in factories is much more difficult than in laboratories and it need substantial experience and know-how in process technologies (PVTEC, 1998). Figure 7 and Figure 8 shows that 10-years of experience of the Program resulted in continuous improvement of solar cell efficiency and large cost reduction.

3.3. Creating market-creation policies (1990-1994)

In the early 1990's, four kinds of market-creation policies for PV were established by the government and the electric power companies: 1) the simplified procedures for residential PV installation, 2) the technical guidelines for grid-connection, 3) net-metering system by electric power companies, and 4) the investment subsidy program for residential PV systems. They are widely recognized as the critical institutional arrangements that supported the PV market expansion the mid 1990's (e.g. PVTEC, 1998). Here we describe

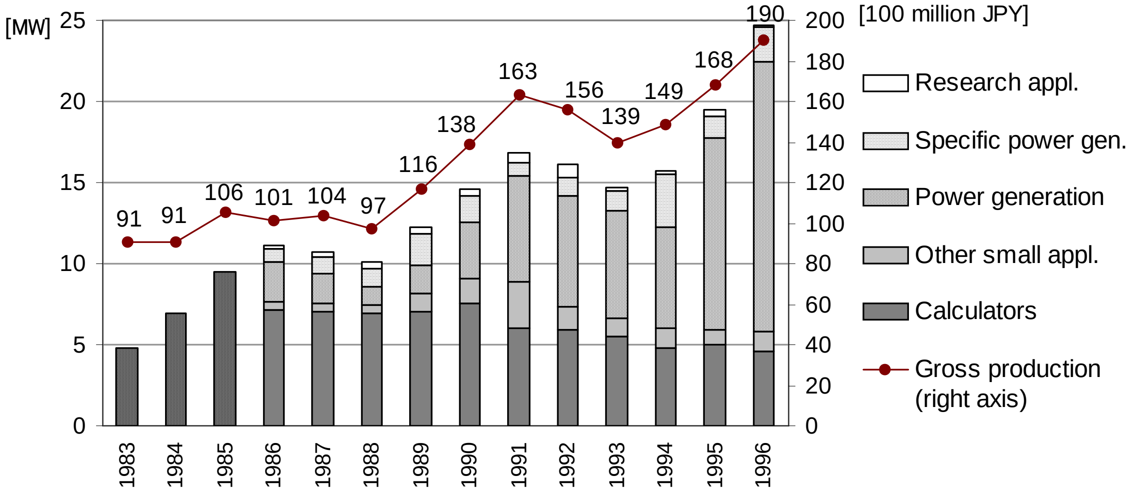


Figure 9 Trend of PV production in Japan, 1983- 1996. *(Source: NEDO 1995; 2000)*

the key drivers of the establishment of these market creation policies.

Ambitious PV producers and their alliance

While the NEDO demonstration projects did provide an indispensable niche-market, it was too small for producers to benefit from. Market for small applications such as calculators was already saturated, and energy applications had only a small share of the total market that amounted only to JPY 10-15 billion market[8] until 1995 (Figure 9). This lack of market made several participant firms in the Sunshine Program, including Hitachi, Toshiba, and NEC, withdraw from PV business in the late 1980's. For these firms growing markets of semiconductors and computers were much more important than the unpromising future market of PV (Shimamoto, 1998).

But several producers, especially Kyocera, Sanyo, and Sharp, all of which are now the top-ranking PV producers, hung on to continue PV development. Their top management had strong commitments to PV development and commercialization. For example, Inamori, who is the founder and former CEO of Kyocera, had a strong intention for PV commercialization[9]. Hayakawa, the founder and former CEO of Sharp, also had a similar strong commitment, and expected a spill-over effect in his company[10]. These producers strongly lobbied for governmental support for market creation. In fact, all of the

[8] Approximately USD 100 million, based on exchange rate of 120JPY/USD.

[9] *"After a few years of the Oil Crises, people became uninterested in PV technology as the oil supply began to be relaxed… But I had no intention to give it up with such little trouble, because I started the PV project with a strong intention to provide a new alternative energy in the future."* (Inamori, 2002)

[10] *"The PV project of Sharp was in complete deficit in the 1970's and 1980's. The reason we could continue the project was the commitment by the top management. The intention of the founder Hayakawa to develop PV was still influential. He believed that PV would be an indispensable technology in the future, and that PV might be a core technology of our company."* (Suzuki, 2004)

market-creation policies mentioned above had been requested by PV producers since the early 1980's. In the late 1980's they established Japan Photovoltaic Energy Association (JPEA), an industry coalition group. Through JPEA they intensified their lobbying activities against the government around the period of 1990 (Suzuki, 2004).

Removing regulatory barriers

Until 1990 there was a regulation by MITI that requires an *Electrical Chief Engineer* when installing a power generation facility with more than 30W capacity. This means, if one wanted to have a solar panel on his rooftop he had to be qualified as an *Electrical Chief Engineer*, which was the same qualification required for large-scale fossil-fuel power plants. While it was clear that this strict regulation had been a major barrier against deployment of distributed power generators, it was not an easy task to remove it due to political inertia and conflict with the electric power industry.

Inside MITI, the Office of Alternative Energy Policy was responsible for developing alternative energy sources. This office played a very important role to remove the barriers. As it was extremely difficult to revise a regulation, both administratively and politically, an officer who served as Chief of the Office from 1988 to 1990, tried hard to create 'momentum' using mass media and governmental committees to remove the regulatory barrier and liberalize the electricity market. He wrote some informal papers that asserted the institutional problem and strongly proposed to abandon the regulation (Ohtsu, 2004). The effort resulted in published articles on several major newspapers[11] in 1989 to 1990 and a special TV program on the Japan Broadcasting (NHK)[12] in 2001. These reports criticized the regulatory barriers and called for simple procedures for grid-connection to expand renewable energy deployment. The momentum was enhanced by discussions in the Committee on Alternative Energy Policy of MITI, which consisted of university professors and industry representatives and was organized by the Office. Guided by the Office's membership selection and agenda setting, the Committee in 1990 recommended that support policies to enhance alternative energy deployment should be established.

In response to rising momentum in mass media and the governmental committee, MITI and electric power companies established simplified procedures of PV installation on June 1990. The subsequent actions by MITI were very quick. In a few years after 1990, MITI established a series of technical guidelines for PV grid-connection.

Technological fix for grid-connection

There was also a technical barrier against grid connection of PV: instability of solar

[11] 4 September 1989, Asahi Shinbun; 6 January 1990, Nikkei Shinbun; 26 January 1990, Mainichi Shinbun. All of them are major newspapers in Japan.
[12] NHK is the public broadcaster of Japan. The program was broadcasted on 7 July 1991.

generation. This was claimed by the electric power industry as the major problem of PV grid-connection. Because stable and reliable supply of electricity is one of the core missions of the electric power companies, they were reluctant to open their electricity grid for small distributed power generators which they could not directly manage.

A large demonstration project by NEDO played an important role to examine this issue. The purpose of this demonstration was to construct 100 house-like buildings with a 2kW PV system each in order to examine their effect on the grid when connected. The project was conducted from 1986 to the early 1990's at Rokko Test Field of Kansai Electric Power Company (KEPCO)[13]. Results of the demonstration research clearly showed that the reliability and safety of the grid electricity could be maintained even when connected to a number of distributed PV systems. Persuaded by the accumulation of data, the electric power industry accepted distributed PV systems to be connected to the grid.

Climate change and domestic energy policy

In the 1980's, there was a growing concern against the climate change issue in the international arena. In 1988, an international conference on climate change that was held in Toronto, Canada, adopted an ambitious voluntary target on emission reduction: 20% reduction from the 1988 level by 2005. Such conferences stimulated many Western European countries to adopt national targets of greenhouse gases emission reduction, e.g. the former West Germany's target to reduce 30% of its emission from 1987 by 2005, and France and Australia to reduce 20% by 2005. But the US was very reluctant to take any action for climate change, and began to be in conflict with some Western European countries. In the first Ministerial Conference on Air Pollution and Climate Change, held in 1989 in Nordvijk, the Netherlands, the disagreement was apparent between some European countries who ambitiously insisted in a commitment to 'reduce' emissions, and the US, who was strongly against 'reduction'. The Japanese government saw the situation highly problematic and proposed a compromise: '*stabilization'* of greenhouse gases emissions at the 1990 level. The proposal was successfully accepted by both of the parties, and the word '*stabilization'* was incorporated in the final declaration of the conference, which they thought was the major contribution of Japan in the conference (Yagishita, 2004).

However, this commitment of '*stabilization'* of greenhouse gases emission, although legally non-binding, constrained the Japanese domestic energy policy. The *Energy Outlook toward 2000*, which MITI was just updating in 1990, showed a steady increase of greenhouse gases emissions in accordance with the growth of energy consumption. In order

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[13] Central Research Institute of Electric Power Industry (CRIEPI) was commissioned to conduct the project, and decided to conduct it in KEPCO's test field, in stead of CRIEPI's own test firld. The intention was that the data from electric companies' own test field was expected to be more persuasive to the industry (Takeda, 2004)

to avoid the inconsistency between the likely increase and the *stabilization* commitment, MITI adopted a very optimistic deployment scenario of renewable energy sources to reduce emissions in the 1990 *Outlook* (MITI, 1990): 250MW by 2000 and 4,600MW by 2010 in cumulative installed capacity of PV. This scenario was extremely ambitious, compared to the actual installed capacity of about 10MW in 1990. As the *Energy Outlook* was a core policy statement of MITI, this assumption was recognized as a kind of governmental target of PV deployment. In fact, in 1994 the assumption was slightly revised as '400MW by 2000 and 4,820MW by 2010' in the 1994's *Outlook*, and the new number was employed as the governmental target of PV deployment (Ministerial Committee on Energy, 1994).

Response by the electric power industry: a voluntary net-metering program

During the 1980's, the electric power companies had been very reluctant (even opposed) to deploying PV and other renewable energies as practical power sources due to reliability and economic reasons[14]. However, the ambitious governmental targets urged them to take actions for deployment of renewable energy sources. On 13 June 1990, just after the release of MITI's *Energy Outlook*, Federation of Electric Power Companies announced that, in line with the governmental target of renewables introduction, the industry would take necessary measures to enhance renewable energy introduction, and that they would start a net-metering system to enhance renewable energy installations by consumers (FEPCO, 1990). They started a net-metering program in 1992 as a voluntary action, buying electricity from residential PV systems at the price of JPY 22 per kW[15], the same as the residential electricity rate. This provided very favorable returns to those who installed PV systems, because typical PV-installed households did not have to pay electricity bills due to the revenue of electricity sold to electric power companies[16].

Adopting the voluntary net-metering program meant a great policy change of the electric power companies from the reluctant attitude toward renewables. One driver was the ambitious target of the government. They regarded themselves as public utilities that served for the public benefits. Therefore, if the government had a strong intention to deploy renewable energies the companies as public utilities also had to cooperate to achieve the policy target. Another reason was that they wanted to avoid regulations. Before the government imposed a mandatory regulation upon the industry, they took a voluntary action in advance, which they could terminate on their own[17].

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[14] Note that the electric power companies have been making considerable efforts on R&D activities on renewable energies since the inception of the Sunshine Program.

[15] Approximately USD 19 cent per kW, based on exchange rate of 120JPY/USD.

[16] A typical 3.5kW residential PV system generates about 3,600kWh a year, which is about the same as electricity consumption in an average household (METI, 2004).

[17] Interview with a senior manager of Tokyo Electric Power Company, Tokyo, 12 August 2005.

Launching a subsidy program for residential PV systems

PV industry had been asserting for years that the governmental financial supports were crucial not only for R&D but also for deployment to create the PV market for energy applications. The industry needed the *first* stimulus to start up a 'virtuous cycle' of increased demand, investments in new production facilities and further cost reduction by economies of scale, which in turn create further increase of demand, and so on. MITI was also aware that a certain subsidy program would be effective in the early stage of market creation (MITI, 1985; 1990). In addition, a German subsidy program, *1000 Roofs Program*, started in 1992, was often referred to as an effective support policy[18], and some promoters of solar energy, including a few Diet members, required the government to adopt a similar support program in Japan[19].

But adopting such a large subsidy program was a controversial task. One reason is that a subsidy for individual properties was unprecedented, and the Ministry of Finance (MOF) was reluctant to accept such a subsidy program. Another reason is the uncertain effectiveness i.e. none was sure how consumers would respond to the program. If very few consumers are interested in having PV systems even with subsidy, the expected increase of demand and cost reduction would not be realized, which would mean a serious problem for MITI and the PV industry.

We now point out four key factors that affected MITI's decision making on this regard. Firstly, there was a broad expectation that the cost of PV production would be rapidly decreased if mass-produced. At that time most part of the residential PV system cost was attributed to that of inverters and other balance-of-systems (BOS), which were then custom-made. So the future cost reduction in inverters and BOS was quite likely by standardization and mass production (see cost structure in 1993 of Figure 10).

Secondly, MITI and NEDO were under strong pressure to bring renewable energies to the market. Despite the fact that the Sunshine Program was already almost 20 years old and that the cumulative governmental investments by 1993 was reaching JPY 600 billion[20], almost none of the technologies had entered the market. There was a growing criticism against this situation, so MITI discussed either to go ahead to the deployment stage, or to terminate it and go back to the basic R&D stage (Fujino, 2004). Seeing the steady technical progress so far and the broad consensus for PV development, the government had to go ahead, investing not only in R&D, but also in deployment.

Third factor was an expectation for consumers' high willingness-to-pay for added values of PV system. Even though the cost had been greatly reduced, it still cost more than

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18 This German program subsidized as much as 70% of the investment cost. See Jacobsson & Lauber (2006).

19 For example, a interpellation by Mr. Seki , a Lower House Member, at the Appropriation Committee of the Lower House, 3 May 1992.

20 Approximately correspond to USD 5 billion, based on exchange rate of 120JPY/USD.

JPY 10 million[21] to install a normal residential PV (Figure 10). The pay-back period of the installation cost was much longer than the expected lifetime of PV even with some governmental subsidies and the revenues from the net-metering system. But some actors, including housing producers, expected that although PV might not be attractive as a power generating equipment, PV might attract some consumers as a high-tech and environmentally-conscious quality product.

Fourth, the *Special Account for Alternative Energy Development* was also a key budgetary source of the subsidy program. In order to start such a controversial program, a budgetary source that could be more easily handled by MITI was necessary[22]. If there had been no such a budgetary source as the *Special Account*, the negotiation with MOF would have been much more difficult (Fujino, 2004).

In this way, MITI finally decided to take the risk to launch a subsidy program, and after tough negotiations with MOF, succeeded in establishing a subsidy program called *700 Roofs Program*, with JPY 2 billion budgets[23] to provide investment aid by 50 per cent.

Summing-up: drivers of the market-pull policy formulation

We now understand several key drivers that promoted the formation of the set of market creation policies in the early 1990's. Firstly, the 20-years history of PV development under the Sunshine Project laid the important foundation. Long-term R&D produced enough accumulation of knowledge and experience, improving PV's efficiency and economics drastically. And the demonstration research on grid-connection provided enough data to assure the reliability and safety of PV grid-connection. Long history of also became a pressure for the government to bring PV to the market in the late 1980's, which urged the government to adopt market-creation policies. The second driver was the efforts by PV industry. They had been investing much more than the governmental R&D subsidies, even though the PV business was in complete deficit in the 1980's, and lobbied to induce governmental supports. The third factor was a 'momentum', enhanced by the Office of Alternative Energy of MITI. It encouraged mass media and the governmental committee to publicly discuss the barriers against PV deployment and contributed to removing the regulatory barriers. The forth factor was climate change debate, which suddenly became prominent in the late 1980's. This unexpected event resulted in an ambitious PV introduction targets by the government, and the ambitious target contributed to change the electric power industry's reluctant attitude toward PV deployment, resulting in introducing the net-metering system. Fifth, there was an expectation for consumers' high willingness to

[21] Approximately correspond to USD 85,000, based on exchange rate of 120JPY/USD.
[22] In Japan a Special Account budget is mostly controlled by a responsible Ministry, whereas the general budget by the Ministry of Finance (MOF). See MOF (2004) for the Japanese budget system.
[23] Approximately correspond to USD 17 million, based on exchange rate of 120JPY/USD.

Table 1 Development of the subsidy program for residential PV systems, 1994-2005.

Fiscal Year	Budget [JPY billion]	Number of: Applicants	Installations	Installed capacity [kW]	Subsidy rate	Average price of PV per kW [JPY million /kW]
1994	2.0	1,066	539	1,900	50%	2.00
1995	3.3	5,432	1,065	3,900	50%	1.43
1996	4.1	11,192	1,986	7,500	50%	1.17
1997	11.1	8,329	5,654	19,486	up to one third	1.03
1998	14.1	n.a.	6,352	24,123	up to one third	1.02
1999	16.4	n.a.	15,879	57,693	up to one third	0.96
2000	14.5	25,741	20,877	74,381	1st) JPY 270,000 /kW 2nd) JPY 180,000 /kW 3rd) JPY 150,000 /kW	0.87
2001	23.5	29,389	25,151	90,997	JPY 120,000 /kW	0.79
2002	23.2	n.a.	38,262	141,438	JPY 100,000 /kW	0.73
2003	10.5	52,863	46,760	173,687	JPY 90,000 /kW	0.68
2004	5.3	61,407	54,475	200,155	JPY 45,000 /kW	0.65
2005	2.6	39,643	--	--	JPY 20,000 /kW	0.64

(Source: RTS Corp., 2006; NEF, 2003)

pay for added values of PV. While none was sure about how the market would respond, MITI took the risk to launch the subsidy program to encourage PV mass-production.

3.4. Market development under the subsidy program (1994-2005)

Right after the announcement that MITI required appropriation for the 700 Roofs Program in the late 1993, PV producers quickly organized mass-production lines for residential PV systems. The three major PV producers, Kyocera, Sanyo, and Sharp, all started to sell 3kW residential PV systems at the price of JPY 6 million. This was an extremely ambitious challenge for the companies, because the selling price was much a lower price than the reported cost in the previous year (JPY 3.5 million per kW). Nevertheless, this was also a great chance for the industry because there suddenly emerged a large market of power application PV, which was expected to be as much as 2MW. That meant 40% growth of the power application PV market (see Figure 9).

The subsidy program attracted much more consumers than expected. In the first year of the 700 Roofs Program, over 1,000 applicants requested the subsidy. In the next year, the program was expanded to a 1,000 roofs program with increased budget of JPY 3.3 billion, and well over 5,000 consumers applied. Seeing the strong response from the market, MITI expanded the subsidy program in the subsequent years. Participants of the program rapidly increased since the program start-up, reaching more than 60,000 of annual installations in the year of 2004 (Table 1). The annual budget was also expanded up to JPY 23 billion (approximately USD 200 million)[24] in 2001 and 2002. On the other hand, the subsidy rate for individual installation was gradually decreased from 50% of the investment cost in 1994

[24] Based on exchange rate of 120JPY/USD.

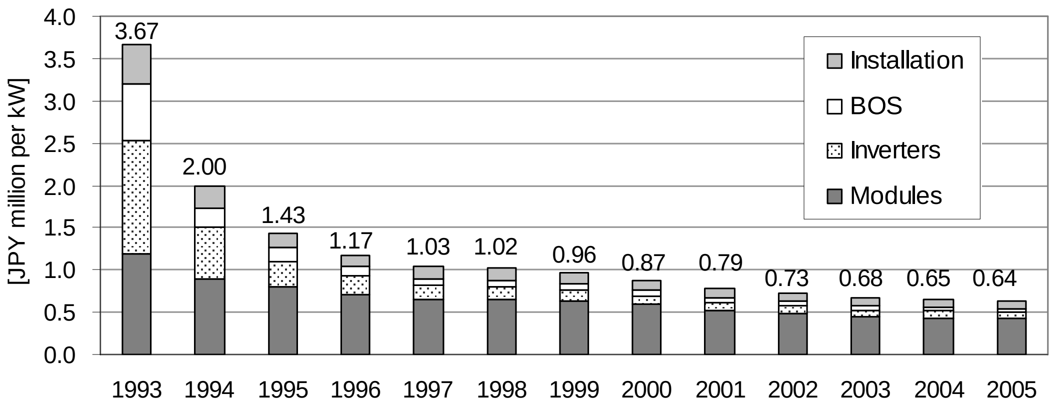


Figure 10 Cost of installing a typical PV (3kW system) in Japan. *(Source: RTS Corp., 2006)*

to only JPY 20,000 per kW or 3% of the investment cost in 2005. The intention was to give PV producers a strong incentive for cost reduction and to maintain a same level of consumers' burden (around JPY 600,000 to 700,000 per kW).

The rapid increase of applicants clearly shows that the program inspired consumers' motivation for purchasing PV very much. In accordance with the expansion, PV production cost was rapidly reduced (Figure 10). Especially the costs of inverters and BOS have been cut down drastically just as MITI and industry expected.

But we should note that, although the cost has been decreased, PV electricity has been much more expensive than the residential electricity rate even with the subsidy[25]. Then a question is: why were so many consumers motivated to purchase PV? Two surveys were conducted in 1996 and 1998 to examine perceptions and motivations of the consumers who joined the program in 1994 and 1995(Iuchi *et al*., 1996; Iuchi, 1999). The surveys also asked the same questions to a reference group of people who were randomly selected in a city, and compared the responses. These surveys show: 1) participants in the program had higher income compared to the reference group (Figure 11). 2) When asked the motivations to purchase PV, more than 90% of the participants pointed 'contribution to protecting the global environment', whereas about 60% pointed 'reducing electricity bills'. In addition, while more than 70% of the participants knew the likely lifetime of PV equipment in advance, only about 30% were convinced of the pay back period and cost per kWh. 3) More than 90% pointed 'the governmental subsidy' as another motivation. The results indicate that PV was accepted by high-income consumers with high environmental consciousness, who are rather indifferent to the cost of installing PV.

PV producers also underscore the same factors in the marketing of PV: affordability of users (or income level), environmental consciousness, and the support of the government. Regarding the last point, the fact that "the government is supporting this product" seemed

[25] Even in 2004 the estimated cost of PV electricity is about JPY 40 per kWh, which is much higher than JPY 22 per kWh of the residential electricity rate (RTS Corp., 2006).

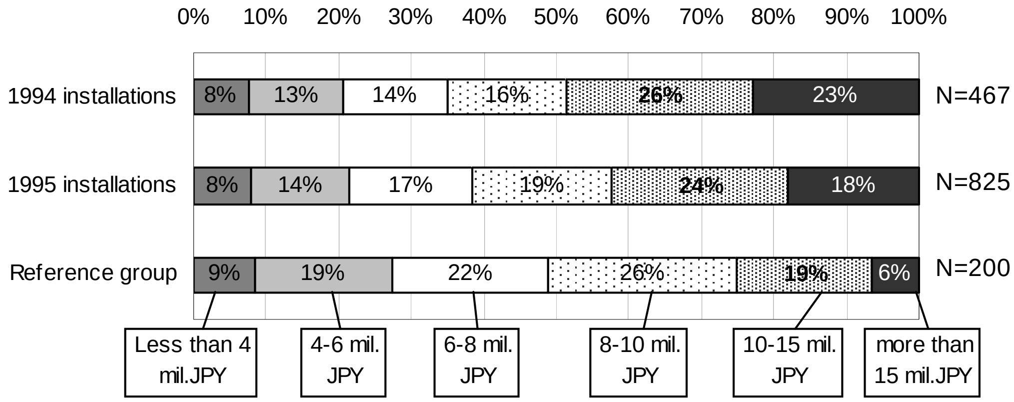


Figure 11 Comparison of family income: households with PV installation and reference group

(Adopted from Iuchi, 1999)

to be a very persuasive factor to convince consumers of social value of PV (Suzuki, 2004).

In sum, the subsidy program, net-metering system, and the PV industry's marketing[26] have succeeded in creating a *niche-market*, where PV is valued more than its value as a mere electricity generator by high-income users.

3.5. Market development without subsidy? (2006 ~)

The subsidy program was terminated in 2005 despite the strong opposition from the PV industry and renewable proponents. The proponents asserted that the government had to keep strong support policies in order to achieve the ambitious target of 4,820MW PV deployment by 2010. On the other hand, there was a criticism that the government had already given too much supports and that the market had to take off without subsidies. In addition, the subsidy rate was already quite a low level especially after 2001[27], which raised a question whether the subsidy was really necessary for market development. Moreover, MITI had declared to MOF (Ministry of Finance) when starting the subsidy program that MITI intended to continue the program until "self-sustaining growth of the PV industry could be achieved" and the target cost was JPY 400,000 per kW (MOF, 2003). The target cost was achieved by a top-runner producer in 2002, which made MITI and MOF determine that the subsidy was not necessary any more (MOF, 2003).

Now that the governmental subsidy was terminated, the only support measure for PV deployment is the net-metering program by the electric power industry. This situation is problematic for PV market development, because the net-metering is not an obligation by the government but a mere voluntary program by the major electric power companies,

[26] The authors have unraveled little about the role of PV industry's marketing. One interesting fact is that the prefecture that have the largest PV capacity installed (and the largest deployment rate per thousand households) in Japan is Nagano Prefecture, where a lot of PV firms are located. This suggests that marketing by producers may have substantial impact on introduction rate.
[27] Subsidy rate was decreasing from about 30% in 2000, 13% in 2002, and to 7% in 2004. See Table 1.

which were regional monopolies until the early 1990's. As they are now facing market liberalization that started in the mid 1990's, they are getting frustrated by the increasing burden which went beyond JPY 8 billion (or 400 MWh) in 2004[28]. It is possible that they would reconsider whether to maintain the current net-metering program, and might result in introducing a less favorable support scheme.

In sum, the governmental support for PV diffusion has been weakened, and the future of the net-metering program by the electric power companies is uncertain due to the ongoing deregulation process. So far Japanese PV diffusion was an early success, but its sustained growth in the future seems to be uncertain.

4. Analysis: success factors so far

4.1. Combination of technology-push and market-pull policies

Our historical analysis shows that governmental supports for PV were of central importance. The key features of the support policies are summarized as follows:

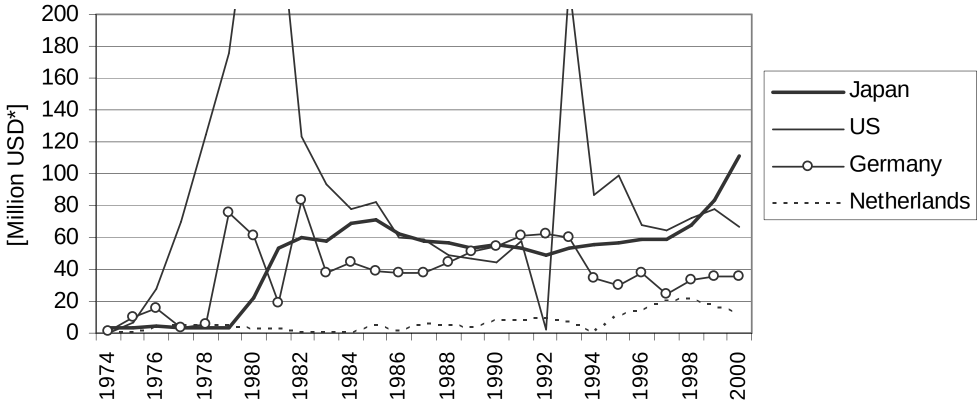
Providing a stable environment for research communities: The government assured consistent and sufficient budgets for R&D activities on PV, which turned out be very important for steady development in a long-term. The stable funding for PV in Japan is in contrast with large fluctuations of governmental budgets in other countries (Figure 12), which turned out to be a barrier for innovation (Margolis, 2002; Christiansen, 2002).

Long-term commitment by the government: This is particularly important for private firms, because it can foster expectation that there should be a market of the technology in the future. In the case of PV, the target of the Sunshine Program was so ambitious that it inspired private firms' investment well over the governmental investments.

Market creation policies: Even if performance and economics of a technology is improving, it takes many years for a new technology to be totally competitive. In order to keep private investments for a long period, not only R&D-push but also demand-pull measures are indispensable. In the case of PV in Japan, NEDO's demonstration projects in the 1980's played an important role as an early market where producers could accumulate production experience. In the early 1990's a set of market-creation policies were established, which succeeded in removing regulatory barriers and convincing consumers to purchase expensive PV equipments, thus creating a niche-market.

Flexible budgetary source: The Japanese experience shows that in order to have a whole set of push and pull policies without budgetary fluctuations, a flexible and stable budgetary source is useful and effective. In the case of PV, revenues from the Electricity Tax (*Special Account*) were indispensable for the expansion of the Sunshine Program as the main

[28] Weekly Energy and Environment, No.1809, 16 September 2004; Nikkei Electronics, No.918, 18 July 2005 (both in Japanese). Data is based on RTS Corp.(2006).



*) US dollars on 2002 prices and exchange rates.

Figure 12 Governmental R&D Budgets for PV in major producing countries. *(Source: IEA, 2004)*

financial source that could be handled by MITI. This was another key factor for the subsidy program to survive more than ten years.

4.2. Market acceptance

Another success factor was that the market (or users) accepted PV in spite of the high price and impossibility of recovering the initial cost even with governmental subsidy and revenues from the net-metering program.

This situation is quite a contrast with the German situation, another example of successful PV deployment. Installed PV capacity in Germany is enormously increasing particularly in recent years and now outnumbering that in Japan (Figure 1), mainly because the feed-in tariff system is providing a very favorable conditions[29] and making PV installations an economically rational behavior for consumers. As described in Section 3.5, results of the surveys on users and comments of PV producers indicate that the current PV market is a *niche*, where high-income home owners with high environmental consciousness are purchasing PV without close consideration of its economics[30]. But, having been a *niche*, which is only about 1% of the whole residential market[31], the residential PV market has a large enough size for PV producers to legitimate huge investments in mass-production facilities, which resulted in substantial cost reduction.

[29] German feed-in tariff for PV electricity generation is EURcents 40-60 per kWh (Wüstenhagen&Bilharz, 2006), which is much higher than JPY 22 (EURcents 16, based on the exchange rate of 135 JPY/EUR) per kWh of the Japanese net-metering price.

[30] A similar phenomenon can be observed in the case of hybrid vehicles (Kurani *et al*., 2006). Based on a number of interviews on hybrid buyers, they conclude that "*Early hybrid buyers didn't buy just (or even importantly) lower private fuel cost. They bought a piece of the future; they bought a less-consumptive lifestyle; they bought the car they believe symbolizes a smart consumer.*"

[31] About 95% of PV systems in Japan are installed on detached houses (IEA-PVPS, 2006), and the number of houses with PV is about 0.25 million (see Table 1), while the total number of detached houses in Japan is about 25 million (Population Census of Japan, 2000).

This fact indicates that a new energy technology does not have to wait until it becomes fully competitive with established technologies before entering the market. If a certain size of a niche market is created it can bring rapid expansion of the industry and technological development. The Japanese PV experience indicates that a niche which is supported by high-income consumers can be prospective as a protected space for immature energy technologies. It might be beneficial for other new energy technologies such as fuel cells, to target such a market.

4.3. Ambitious private firms with strong commitment

Private firms, such as Kyocera, Sanyo, and Sharp, played critical roles in the development process of PV technology. These ambitious producers acted as “prime movers” (Jacobsson & Johnson, 2000: 630), investing in-house resources in R&D much more than governmental subsidies and lobbying the government for creating market-pull policies. Such aggressive efforts are in contrast with some other participant firms of the Sunshine Program, such as Hitachi, Toshiba, and NEC, which terminated PV development in the late 1980’s because of the lack of market and priorities on other growing technologies. This indicates that private firms with strong commitment by top management are indispensable to overcome a long, hard time that is inherent in a new energy technology development.

The reason of the strong commitment of these ambitious firms is largely a matter of business judgments by top management, but it was also influenced by the governmental target and policy framework that were intended to create PV industry in the future.

4.4. …And a little luck?

At least a part of the successful development of PV was a result of certain ‘luck’ of the history. The development process was far from being determined, but was influenced by some unexpected events and unintended consequences.

For example, in the 1970’s PV development was only a small project in the Sunshine Program because at that time solar thermal power generation was the most promising technology. But, by luck, the solar thermal power generation was failed, and this made PV the Program’s major focus in the 1980’s. In addition, the second Oil Crisis, another unexpected event, urged the government to accelerate the Sunshine Program and to establish the Special Account for Alternative Energy Development. The stable and sufficient budget of PV after 1980’s owes a great deal to the unexpected emergence of the Special Account as the major funding source. Also, the emergence of a PV niche-market in the high-income households was completely unpredictable because none was sure how consumers would respond to the subsidy program and before launching the program.

We do not mean to say that the technology development was completely by chance, but only to assert that the technology development is inherently an uncertain process, and that at least a part of the PV development process cannot be explained without certain luck or coincidence.

5. Conclusion

30 years of PV development in Japan was a co-evolution process of the technology, support policies and the market. The technology in the laboratory stage was rapidly improved in its efficiency and economics over the 1970's and 80's, entered the market as a power application in the early 1990's, and after that the industry continues to grow rapidly, in accordance with the establishment of various support policies and the market acceptance. Now the Japanese firms have the top market share and the installation is in rapid increase. PV development in Japan is clearly a successful case of new technology development, at least so far.

The case study shows that the combination of technology-push and market-pull policies is indispensable for new technology development. These policies need to be backed up by strong commitment by the government and provide a long-term, consistent framework in order to foster expectation for future market of the technology. Such expectation induces private investments that can be much more important than the governmental investment itself.

The study also shows the importance of a niche market. New energy technologies do not have to be totally competitive with incumbent technologies when entering market. Finding a niche where the technology is selected by users due to its added values is a critical factor for the development. For consumer goods like residential PV, a niche that is supported by high-income consumers with high environmental consciousness can be an effective target.

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