The International Adoption of Photovoltaic Energy Conversion

Is Japan a Lead Market?

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February 14, 2004

Abstract: This paper explores on the basis of a case study on photovoltaic energy conversion (PV) whether countries can actively create a lead market for new technology. Solar energy conversion has fascinated people and politicians as an alternative to oil and nuclear energy. Since the discovery of photovoltaic cells that directly convert solar irradiation into electricity it is expected that the mass market for photovoltaic energy conversion will emerge soon. With lots of sunny, flat and vacant regions and an electricity-hungry and high-income population, the United States looked to be the natural lead market for solar energy. Yet, two countries that are less favorably endowed with solar energy, Japan and Germany, embarked on establishing a mass market for solar energy conversion through high public subsidies. This paper discusses the prospect of these two countries to set off a bandwagon among all other nations? Reviewing the traditional mechanisms of the international diffusion of innovations, the tentative answer given in this paper is that while local markets have been created, this has not ensured the international success of PV. For its international success, it would be essential to demonstrate that the adoption of PV systems is continuing without subsidies. With the energy production cost of solar cells unlikely to come close to that of conventionally generated electricity in the foreseeable future, the United States looks like the test market for solar energy, where the fate of PV will be answered.

Keywords: Eco Innovations, International Diffusion, Photovoltaic
JEL Classification: L80, C53, F14, O31

Acknowledgments: This paper is based on the research project: "Policy-Frameworks for the Development of International Markets for Innovations of a Sustainable Economy - from Pilot Markets to Lead Markets" for the Federal Ministry of Education and Research, grant number 07RIW1A. I would like to thank Klaus Rennings for valuable comments. Some statements are based on discussions with Mr. Yobayashi of Showa Solar Energy K.K., Mr. Nakajima and Mr. Nishida of the Japan Photovoltaic Energy Association and Mr. Goto and Mr. Tsuji of Kyocera Corp.

1 Introduction

Photovoltaic solar energy (PV) is a fascinating alternative as a renewable energy. It is clean and silent and the main resource is obtained without any production and transportation cost; thus it is seemingly ideal for reducing CO_2 emissions. However, the panels that convert solar radiation into electrical power are costly and energy intensive to manufacture, rendering electrical energy from PV cells one of the most expensive of all non-renewable and renewable resources. This is why its usage beyond certain niches remains marginal. It is still unclear whether the adoption of PV as a considerable energy source beyond niches will ever take off. This paper addresses the prospect of solar energy from the perspective of the ability of single countries to render this technology internationally successful, that is whether the success of photovoltaics in one country can ensue its global success. The reason for this approach can be found in the effort of some countries, most notably Japan and Germany, to direct the widespread domestic adoption of solar cells to supply electricity for households. In order to assess the chances that single countries can propel a technology to global success, the paper discusses the factors that could drive a locally successful innovation abroad. At first glance, Japan and Germany do not look like the natural lead markets for photovoltaic energy conversion compared to the United States. Unlike the first two countries where sun irradiation is rather low, PV cells are more profitable in the US with its large, sparsely populated regions endowed with high sun irradiation but where remote households are often not connected to an electricity grid. Large developing countries such as China and India face a similar problem of electrification and are, therefore, future export markets.

Yet, solar energy would not have a chance on the world market without governmental intervention. Although governmental intervention to increase the export success of a domestic technology is tarnished as unfair trade policy, the character of solar energy as an environmental technology opens the door for politicians to use their tool box to organize a domestic success that is often necessary for an innovation's global competitiveness. Negative externalities of non-renewable energies and an anticipated shortage of oil call for governmental support of renewable energy. Since the first oil crisis many countries, including the US, have introduced support programmes to kick off a mass market for PV cells. What Japan and Germany have managed so far is to create a vibrant domestic market with limited international effect. This paper discusses the question of whether a national government is able to create a lead market for photovoltaic energy conversion, that is, a domestic market that will be followed by other countries.

The analysis of the international leverage effect of countries for photovoltaic energy conversion discussed in this paper is based on the theoretical approach of Beise et al. (2003) and Beise and Rennings (2003). First, the international diffusion of PV systems from the PV cell's invention up to 2002 is discussed and the differences from country to country are explained with a simple regression model. In the following section the factors that might push a specific technology to commercial success abroad are discussed for the case of PV. The tentative answer to the main question given in this paper is that the international success of PV is not considerably supported by its domestic success in Japan and Germany, because those countries have little lead market potential. The only potential leverage Japan has is cost reduction. With the energy production cost of solar cells unlikely to come close to that of conventionally generated electricity in the foreseeable future, this leverage effect seems to be slim, however.

A lead market is interpreted here as the regional market where the fate of an innovation is decided. If its sells there, the potential for global success is high; if it fails there, there is little chance for a global success either. In that sense of a lead market, the United States is the lead market for PV, that is, the market where this question about the merit of PV as terrestrial energy source can be answered.

2 The Diffusion of Photovoltaic Energy Conversion

2.1 PV History

Photovoltaic energy conversion is the generation of electrical energy for households and industry by photovoltaic cells. This definition excludes all applications of PV cells in small devices such as calculators. PV power generation has seen a dynamic development in the 1970s and again in the 1990s, spurred by the subsidies of governments frightened by the leverage of the OPEC cartel or pushed by increasing public perception of risks caused by global warming or nuclear energy. The invention of PV cells, however, goes back to the 19th century. Photovoltaic energy conversion is based on the photoelectric effect discovered by Edmund Becquerel in 1839. Albert Einstein was awarded the Nobel Price for explaining the effect in an article published in 1904. The first solar cell that converted radiation of light into electric energy was developed in 1883 by an American inventor, Charles Fritts. The commercialization phase of PV cells started in the 1950s after the transistor effect was discovered and explained. Pioneering work was done by AT&T and RCA of the US in the field of both crystalline and amorphous silicon (Johnstone 1999, Grupp 1997, p. 373). PV cells were commercialized mainly in the United States and by American companies because the first PV cells were very expensive and demand came virtually exclusively from the space industry to supply energy for satellites. However, other countries such as Japan, Germany and France entered the emerging PV industry already in the 1960s. For instance, Japan equipped a light house with a 242 W PV system in 1963 with PV cells manufactured by Sharp.

With the oil crisis in the 1970s governments in the industrialized world have initiated support programmes for research on and adoption of PV power conversion. Governments have supported the PV industry in various ways. All common instruments were used: research and development subsidies, political endorsements and target setting, demonstration projects and market stimulation incentives. R&D subsidies have the longest history. First, military and space related programmes were introduced in the US leading to the first PV cell powered satellite in 1958. R&D programmes around the world were introduced in the 1970s when the PV technology was still in its infancy and only expensive and low efficiency PV arrays were used. The public R&D budget was especially large in the United States, with federal support for terrestrial photovoltaic application in the 1970s and the massive funds generated by the Solar Photovoltaic Energy, Research, Development and Demonstration Act introduced in 1978. Germany and Japan took a similar path starting in the early 1980s. Japan, depending heavily on imported oil, initiated the Sunshine Program in 1973 but serious R&D support began after the second oil crisis at the end of the 1970s. Public R&D spending for PV climbed rapidly from around 1 billion yen ($4.5 Mio) in the late 1970s to 7 billion yen ($60 Mio.) in the 1980s and 1990s (Watanabe et al. 2000), slightly more than the federal R&D budget in Germany. The heavy spending lasted officially until 2003, but the Ministry of Trade and Industry has found ways to continue the financial support beyond the planned cessation of public funds.

On the demand side, financing of demonstration systems and direct subsidies for private users were widely used by governments as policy instruments to support the adoption of PV energy conversion. Market incentives were introduced in the late 1970s. In the US, the Energy Tax Act of 1978 established a 10-percent investment credit for photovoltaic applications. Broad terrestrial PV energy conversion started in the 1980s. Large PV panel facilities with more than 1 MW peak power were built in the United States; the biggest ever was Carrisa Plains with a capacity of 6.5 MW. Other countries as well put their hopes into large PV systems. Yet, when in the mid-1980s the OPEC threat waned and oil prices fell back to their pre-crises levels, interest in PV energy conversion faded as well. The large PV fields were not extended as planned but dismantled when they reached the end of their life cycle.

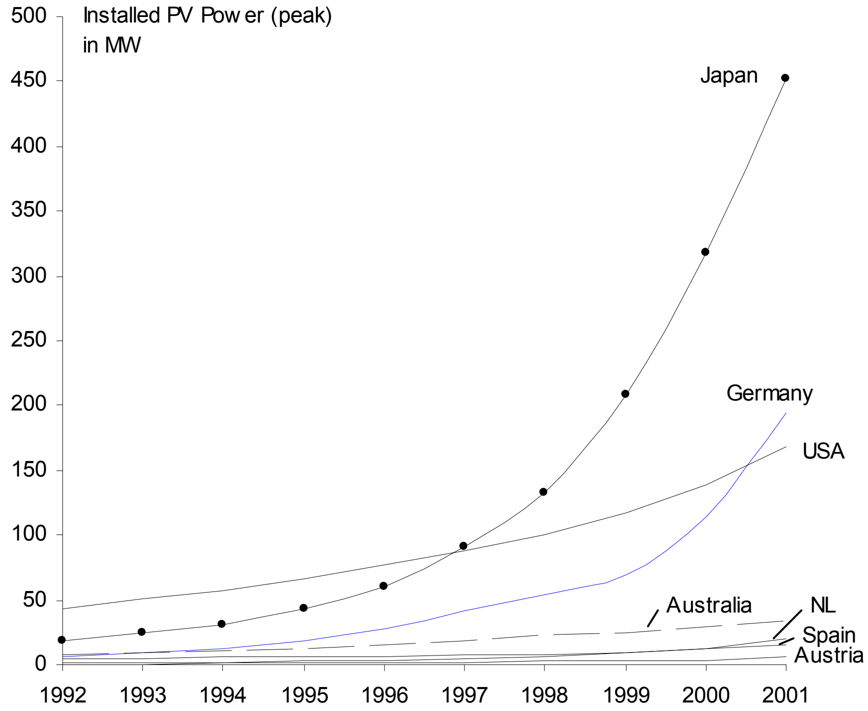
In the 1990s, however, the global warming issue boosted public support for PV and led some European countries and Japan to promote grid-connected photovoltaic systems as an alternative electricity source for households. Direct subsidies were given as tax credits or preferential loans and direct cash rebates for PV systems. The biggest programs are the roof-programs in Germany, Japan and - introduced only recently on the federal and state level - the USA. Japan's government initiated the New Sunshine Program in 1993 to promote PV technology and the residential dissemination program to subsidize the adoption of small grid-connected PV systems for residential houses. Germany and Switzerland - with some European countries following the lead of the trio - introduced low interest loans and high feed-back rates for decentralized solar electricity generation of roof tops. Direct investments attract house owners and other small investors who lack access to financial markets. Subsidies are commonly up to 50 % of the total cost of a PV installation (Goldstein et al. 1999). Apart from direct subsidies, the most successful instrument in terms of adoption of renewable energy generators by private investors has been the renewable-energy-feed tariffs or buy-back rates. Feed tariffs are government-set purchase prices which utilities must pay for electricity produced from renewable energy facilities. Mostly, a preferential feed-in rate or "net metering" is offered, which means that electricity sold and purchased by the utility are equally priced. These subsidies, however, are not sufficient to make PV economically profitable for the user and some environmental commitment is required. Germany, however, introduced the most generous feed back tariffs in 1999 with five times the retail price for electricity, rendering it profitable for private ventures to build (other countries have set an equal or lower tariff). The high feed-back rates in Germany have not only attracted house owners but also investors to once again construct large centralized PV fields with up to 4 MW peak power.

2.2 The diffusion pattern

The adoption of PV cells can be quantified by power of the cumulatively installed PV cells at their nominal maximum or peak power. Figure 1 shows the build-up of PV power systems in several countries. Yet, this figure depends on the size of the country, underestimating the effort of small countries. The penetration rate as a measurement (e.g. application per population) controls for the size of the countries, making it easier to compare the countries based on their preference for a specific innovation. The penetration rate for photovoltaic energy conversion in the local market is characterized in this paper not as PV installed per household but as the ratio of installed power at peak and the electrical power equivalent of the solar irradiation in the respective country during one year. The latter is the power of solar irradiation that reaches the surface of a country in a year's interval. What is quantified with this ratio is the degree of usage of the available solar power within a country. Taking the sun irradiation as the denominator, therefore, controls not only for size but also for availability of solar power. Although not all sun irradiation can be converted into electrical energy by PV cells (there is a theoretical maximum efficiency of around 32 %), the efficiency depends mainly on the cell technology and to a much lesser degree on the geographical characteristics of a country. Two measures for the maximum electrical power of the sun usable in a country are possible, one that multiplies the average solar irradiation with the whole surface of a country and one that takes only the surface of roofs of buildings into account. The first indicator relates solar energy usage to all parts of a country as usable in principle; the other considers only roof tops as relevant as locations of PV cell arrays. Because there are considerable differences from country to country depending on which measure is used, both have been used in the analysis. In Figure 2 the penetration rates of PV cells of the top 5 countries is depicted using the total surface as reference.

Although data is only available for the 1990s, the graphics indicate that the United States used to be the market with the highest volume of installed PV power until the mid-1990s. Switzerland was the country with the highest ratio of usage and sun irradiation. This long time lead of one country resembled the general pattern of the diffusion of an innovation and it is not surprising that the

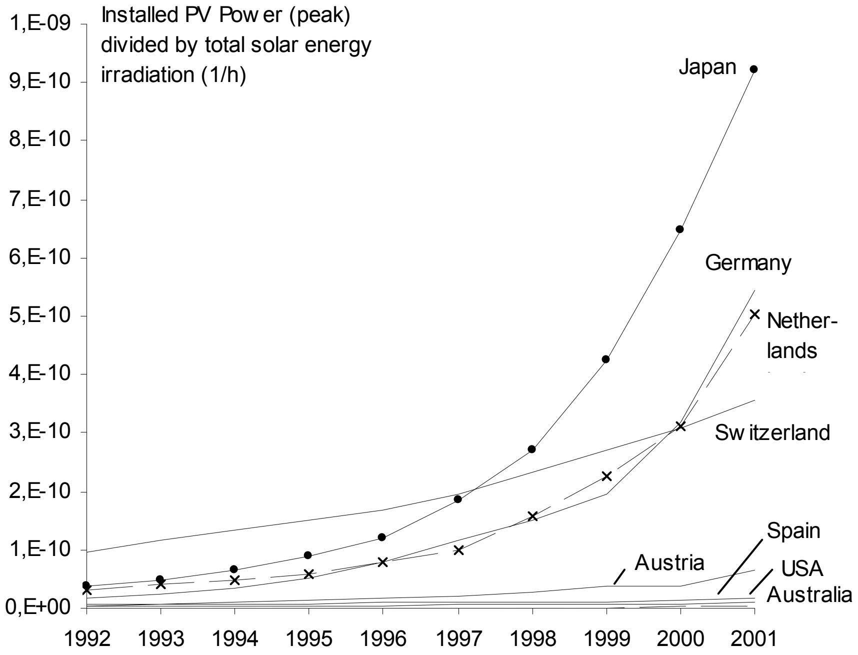
Figure 1: Installed PV power 1992-2001 by country



Source: IEA

US was the country that started the PV diffusion. However, in the second half of the 1990s an unusual pattern emerged. The United States was overtaken by two countries in terms of installed PV systems and Switzerland in terms of penetration rate. This dynamic shift by these two countries to the forefront of PV energy conversation reflects successful governmental intervention in the form of direct subsidies, low-interest loans, and high purchase prices for PV based electricity. A side effect of the subsidies was a shift in the structure of PV applications. While until then stand alone systems were the main application of PV, grid-connected roof top systems of private houses and commercial buildings became the main application of PV panels (see below). Yet, these two countries did not remain alone. Other countries in Europe followed in the late 1990s, mainly Spain, Austria and the Netherlands, by introducing similar support programmes. And most states in the US have re-established support "roof programmes" for PV systems as a reaction to local energy crises and worries about the dependence on oil from the Middle East. Germany and Japan have succeeded in creating a large domestic market for PV with high growth rates. Both use direct subsidies. While Germany uses high feed back rates, Japan introduced a string of supporting measures. Governmental and public institutions were urged to install PV systems at facades and on roofs. In addition, PV systems were declared as building materials which opened tax-credit benefits and other preferences given to new

Figure 2: The Diffusion of Photovoltaic Power Installation 1992-2001 in several countries



Source: IEA, own calculations

housing to PV installations. These various incentives created a lively market for PV. However, in all countries the PV market is still dependent on the retention of subsidies (Holihan 2000), which is apparent when support programmes are due be phased out. At the time the roof programmes in Germany and Japan were scheduled to be stopped in 2003, the domestic PV industry anticipated a strong decrease in demand and voiced new programmes to prevent the otherwise inevitable layoffs or even the destruction of the whole industry that was fostered by public funds.

Since only a few countries use PV panels to generate energy to a considerable amount, it is arguably not really a globally successful innovation. Two countries, however, have shown that in the presence of strong governmental commitment the PV industry can flourish and be considered locally successful. In the third chapter I will discuss the internationalization mechanisms that those countries might initiate. Before, the effect of the various policy instruments on the nationally preferred design of PV energy conversion and the competitiveness of local industry is discussed.

2.3 Competing PV Designs and Policy Instruments

In almost all innovation ideas there are initially alternative designs that compete to become a globally dominant design. A design is a technical specification of an innovation idea (Utterback 1994). The fax machine and the teletypewriter, for instance, are different designs for transmitting a text electronically. Designs compete on different levels. There are different designs of PV cells, but PV cells themselves compete against wind energy in the field of alternative energy. In general, different designs have different merits from country to country, so that countries would prefer different designs. For instance, countries in the sun belt would prefer solar energy among sources of alternative energy whereas countries with a windy coastal region prefer wind energy. Yet, standardization advantages push for convergence and often globally dominant designs appear. The country that has initially preferred the design that becomes the globally dominant design can be characterized as a lead market (Beise 2001). Within governmental regulation specific designs are more or less supported. It is difficult to introduce an effective environmental policy that has no design bias at all. Often governments deliberately support one design over another to enhance the effectiveness of the intervention and the competitiveness of the local industry on the international market. This is called "picking the winner", because governments aim to promote at an early stage the innovation design that will become the global dominant design enabling export opportunities for the domestic industry.

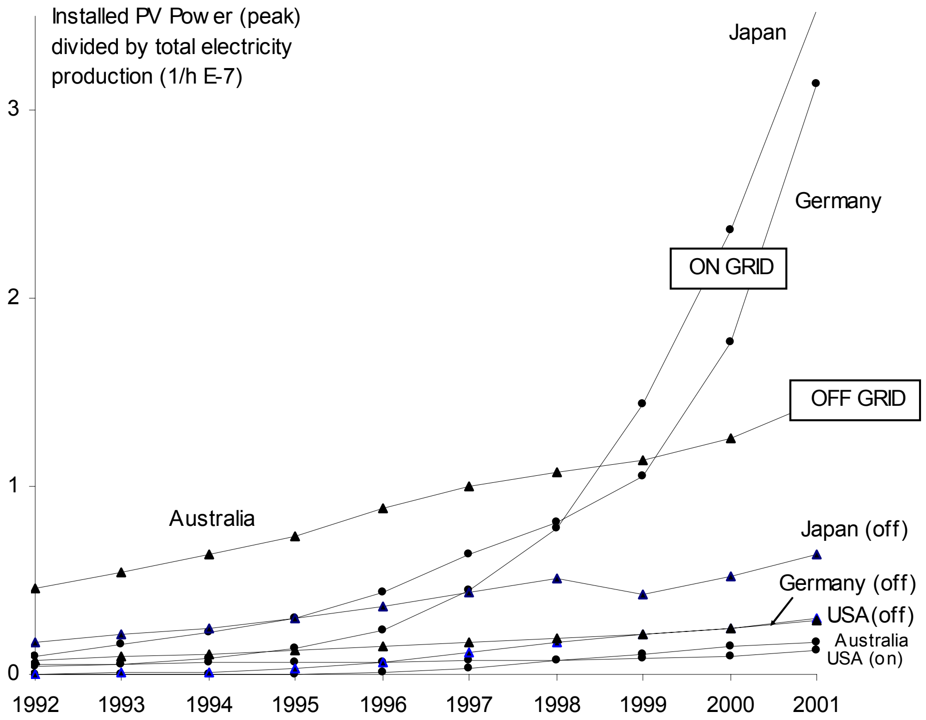
In Japan, environmental policy is derived from a combination of domestic environmental problems, the longing to reduce the dependency on oil and the governments sense of obligation to create new internationally competitive industries. This motivation led the government to invest considerable money in photovoltaic energy conversion. Photovoltaics are most appealing compared to other types of alternative energy because Japan has already a large semiconductor industry and PV cells are used for electronic devices such as calculators. Wind energy in contrast receives little public support. An official of the Japanese Ministry of Trade and Industry (METI) explicitly mentioned as one reason the fact that in that case wind generator technology would have to be imported from Europe. Although there is not much wind in Japan, average solar irradiation in Japan is lower than in most other large countries as well. Another indication for the political choice of photovoltaic is that PV does not help reduce oil dependency or CO2 reduction. The favorization of photovoltaic energy conversion seems more due to the strategy of world market domination as mass production is expected to be capable of driving down costs of production to a level that makes PV cells competitive for all kinds of applications.

The bias of governmental regulations towards specific innovation designs in alternative energy affects the technical choices to be made within PV technology as well. Within the photovoltaic technology, materials as well as system designs compete to become the dominant design. On the material side, traditionally, the United States market favored the most expensive crystalline silicon because applications for extra-terrestrial and remote locations dominate, which require high-efficiency cells. In contrast, Japanese companies have always looked for a cheap substance for mass market applications, such as calculators and other appliances, and it was expected that amorphous silicon or thin film would do the trick. Europe somewhat settled in the middle between the two extremes using and producing mostly poly crystalline silicon. Yet, the domination of crystalline silicon as the basic substance for PV cells appears to be much more stable than anticipated. In 2001 it still held a market share of 90 % with a growing share of poly crystalline silicon (cf. A. Räuber, PSE). The large scale production of amorphous silicon and thin-film PV cells faces many technical problems not expected after successful trials in the laboratory. Therefore, Japan was unable to start a bandwagon mass market based on cheap mass-produced PV cells. It appears that Japan's lead market potential relies solely on a technical breakthrough towards cheap PV cell production.

While governmental subsidies for the adoption of PV cells had less influence on materials for PV cells, it influenced the adoption of specific system designs. First of all, public subsidies in the front-runner countries for PV energy conversion are given explicitly for PV systems and feed-back rates in Germany are much higher for PV than for wind generators. In contrast, the EU policy aims to increase the usage of renewable energies in general, reflecting the diverse preferences within Europe. Second, most subsidies give preference to the adoption of proven older systems over new and unproven designs since the user receives an initial financial contribution and normally has to bear all the maintenance cost. And third, as already mentioned above, feed-back rates that have been applied so successfully in those front runner countries are only supporting the adoption of grid-connected PV systems. The result of this policy instrument is that grid-connected systems attracted all the capital for PV leaving non-grid connected technologies with little support to develop as well. Figure 3 shows that the dynamic growth of PV energy conversion in Germany and Japan is solely due to grid-connected systems. Countries that offer only cash subsidies but no feed-back rates, such as Australia and the US, have lacked the dynamic of investments in grid-connected systems and remain focussed on off-grid applications. The mixture of incentives in Japan has led to a variety of off-grid and on-grid PV systems, whereas in Germany the extraordinarily high feed back rates resulted in a dominance of grid-connected systems.

In contrast to this market vigor in the two front runner countries, experts consider the non-grid connected market as the main global market (e.g. Fuhs, 2000) since in regions with no access to the electricity grid, where still 30 % of world's population lives, PV cells are or have the potential to become economically competitive against other generator types such as diesel engines (Holihan 2000). Off grid is also the biggest market in the United States. The US government expects that the market share for grid-connected applications in the domestic market will remain low, around 17 %, in the year 2020(as cited by Holihan 2000). In addition, the expected surge of PV applications due to region-wide electricity breakdowns, such as in California, the US and Italy in the 2003, are again associated with battery-equipped non-grid connected systems. Although PV systems are modular in the way that different applications (grid-, non-grid-connected) share the same components, companies that focus on grid-connected PV systems face design-mismatch problems in the non-grid-connected market. First, grid-connected systems neglect the electricity storage technology that is important for

Figure 3: On-grid and Off-grid Applications in Germany, Japan, the USA and Australia



Source: IEA

non-grid but not for grid connected technologies. Second, connection to a public electricity grid requires a high quality AC-DC converter, since PV cells generate DC currency. For stand alone generators, either DC or a low quality converter is sufficient.

Therefore, taking the design issue seriously, the successful policy measures that led to the establishment of a domestic PV market in Japan and Germany are not in true accord with the market in countries that do not subsidize PV applications or that have no dense national grid. As long as there is no policy diffusion, this could be regarded as the world market.

However, while in Japan the on-grid market is the most dynamic market as well, it's PV policy supports a broader, more versatile technology foundation compared to the European countries where the focus is solely on grid-connected systems. Japan has not only the largest installation of on-grid PV systems but also a larger volume of non-grid applications than the US (figure 3). Only Australia has a higher capacity of off-grid PV power. Because of PV modules for space applications, Japan also has a large production of the expensive mono crystalline cells, and the continuous PV applications in small appliances such as calculators keep research for amorphous silicon alive.

There are two problems if a country pushes a technology with direct subsidies for the user. The first is that users in other countries expect that the application will be profitable for him only when subsidies are given. Second, the public subsidies often favor one design or application. The transfer of a technology from one application or design to another unproven application or design in another country is more difficult than transferring the same design or application from country to country. In the PV industry this transfer across applications is often suggested as the successful path to world wide adoption (e.g. IEA 2000, p. 64). In practice it is difficult to sell a technology for mass market usage that worked only in a niche application. Only grid-connected PV systems benefit from attractive pay-back rates. This puts PV energy conversion in direct competition with electricity production in central power stations and it is unlikely that this application will ever be profitable without subsidies. Although the transfer of grid-connected to non-grid connected applications is supported by the modular character of a PV system, a company that focuses on grid-connected solutions such as the European manufacturers in Europe will have problems with exporting their systems to countries that use mostly non-grid PV systems.

2.4 Domestic markets and the success of manufacturers

It has often been suggested that differences in market penetration of PV cells affect corporate competitiveness. Porter (1989) describes local demand structure as one of the main nation-specific competitive advantages. User-producer-interaction theory, starting with Linder (1963) and further developed by Lundvall (1988), suggests that a dynamic local market rewards local companies more than foreign companies because of the efficiency of regional and cultural closeness for the perception of market preferences, communication with customers and feedback. The hypothesis has been supported by empirical studies on the micro level(e.g. Gemünden 1981, Cooper and Kleinschmidt 1987). If the local market has a lead role in the world, that is that other markets follow its lead, then local firms are expected to profit more than firms in other countries. Their export performance should be better than that of other companies in the industry.

The PV industry, however, had to constantly adjust to changes of regional market dynamics, technological developments and varying intervention of national governments, accompanied by a continuous consolidation of the PV cell manufacturing industry. The shift in ownership of PV cell production reflects the swings in regional market dynamics. From the beginnings of the industry until today, a positive correlation between the local market dynamic and the commercial success of local firms becomes apparent. Initially, the PV applications in satellite application created the first market for PV cells which gave US companies such as Arco Solar and Solarex a head start. They dominated the market for PV cells until the 1980s. With lots of sunny, flat and vacant regions on the one hand and an electricity hungry and high-income population on the other hand, the United States always looked (and still looks) as the natural lead market for solar energy, that is one untainted by governmental intervention in the adoption process. Yet, the lagging dynamic of the US market since the late 1980s has led

US investors to leave the solar industry and to sell production facilities to foreign companies, notably to Siemens and ASE of Germany, and Sanyo and Kyocera of Japan. A boom in PV production in Europe initiated by national subsidies for the installation of solar cells opened large export markets for US and Japan manufacturers until sufficient production capacity could be built up in Europe. Yet, when the public programmes in Europe were temporarily phased out, PV cell production was reallocated to the US market again.

The late 1990s saw another consolidation process of the industry. By this time, the large European oil companies, BP and Shell, bought large chunks of PV production capacity. In Japan, Sharp aggressively invested in new production facilities and became worldwide the largest PV producer. In 2001 those three companies and Kyocera of Japan were in control of almost 60 % of the world production capacity of PV panels with most of the other producers based in Europe and Japan as well (source: Photon International). Concerning production location, Japan holds the lead with a 43 % share of worldwide production. The United States' share decreased to about a quarter of the production of PV cells, down from 40 % since the mid 1990s, while Europe increased its share to 23 % (Butz 2002). Europe is still a net PV cell importer; its biggest market, Germany, imported more than half of total domestic installations in 2002 (IEA 2003).

The export success of PV cell and module exporters is still concentrated on grid-connected systems in the markets that subsidize PV applications (European countries and Japan). Japanese manufacturers made little progress so far in the non-grid connected market, confirming the problem of design mismatch described above.

3 Factors of International Diffusion

3.1 Explaining the adoption of solar energy

In this section some basic factors that can determine the adoption of photovoltaic energy conversion by country are discussed and tested in a simple regression model. The aim is to explain the international differences in the penetration of PV energy conversion or why a country adopts PV cells more widely than other countries. To assess the question of whether other countries will adopt PV cells over time as much as the leading countries, it is essential to indicate the main adoption factors for PV. In the following section we discuss whether these factors are likely to spread worldwide. The front runner countries are the lead markets if the conditions of a country that let local users adopt a specific technology lead to increased incentives for users in other countries to adopt the same technology.

The historical overview already demonstrated that the regional adoption of PV cells had nothing to do with technological gaps between countries. Although PV technology may be science-driven or science-related (Pavitt and Soete 1994), differences in adoption from country to country cannot be explained by differences in technological knowledge endowments among countries. The technological progress in photovoltaic technology was spurred by researchers and technicians in the US, Europe, Japan and Australia. The scientific and technical knowledge normally spreads worldwide quickly by articles published by the scientific community. In addition, the success of cell efficiency achieved in laboratories regularly means nothing for the efficiency of cells produced for the mass market. The productivity of production technology and, especially, the failure rate are the factors that determine the success of a manufacturer. And the incentives to invest in production facilities are normally determined by the local market size.

The main incentives for adopting a technology for a country in the first place are expected to be the sun irradiation (the benefit) in the country, the price of the innovation, the price of substitutes (electricity) and governmental incentives.

The relevance of these factors for the adoption of PV panels is tested using a simple linear regression model. The endogenous variable is either installations of PV panels in MW divided by the total electricity production in MWh or divided by total solar irradiation in MWh per year. The solar irradiation is measured in MWh per m^2. The average system price of PV panels per kW for systems with more than 10kw and the price of electricity for households is provided by the International Energy Agency (IEA). All prices are converted to purchasing power parities US-$. The IEA also made estimations on the financial contributions of governments to photovoltaics in the form of R&D funds, demonstration projects and market subsidies. All data is for the year 2002. However, data is only available for 13 countries, which renders the regression rather unreliable. Therefore, a panel regression for the years 1992 to 2002 was estimated. The panel includes 142 observations and allows for control of country-specific factors. The problem with a panel estimation is that the system price is only available for the year 2000 and the governmental funds for 2002. Therefore, the module prices are kept constant over the 10 year period and only the R&D funds are retained, because those are the only funds that do not vary considerably during the 1990s and they are an indicator of the overall effort of governments to support PV energy conversion. While prices for PV systems decline continuously over time it is assumed that the international price structure remains the same. The data of 2000 are thus used as a proxy for the price differences from country to country for the whole period. For the panel estimation a random effects GLS regression is applied. Only the results of the regressions with PV installations divided by electricity output as an endogenous variable are presented in the following table (results with the other variable are similar).

Tab 1: Regression results for PV installation as a share of total electricity production

	OLS Reg. for 2002		GLS Reg. 1992-2002	
	Coefficient	t-Value	Coefficient	t-Value
Exogeneous Variables:				
Sun irradiation	0.027	0.27	0.074**	1.99
System price	-0.023	-1.67	- 0.011***	-2.82
Electricity price	-0.158	-0.17	0.433	1.39
Public R&D budget	0.536	0.65	0.629**	2.18
Demonstration	5.727	1.66		
Market stimulation	1.581*	2.02		
year			0.013***	7.87
Constant	0.204	1.01	-27.53***	-7.90
/sigma_u			0.032	
/sigma_e			0.061	
rho			0.218	
No. of Obs.	13		142	
R^2 *Adj.*	0.78			
R^2			within 0.365	
			between 0.726	
			overall 0.505	

All coefficients have the expected sign. However, due to data constraints, the estimations for the year 2002 are mostly insignificant. Only market stimulation funds have a significant effect of market penetration. In the panel estimation, most coefficients are significant. Only the electricity price has no effect. This seems to be caused by the high electricity prices in the Nordic countries where wind energy is used as the preferred alternative energy source. The results show that governmental instruments can create a home market for a technology even if there are natural disadvantages, in this case lack of solar irradiation. Among the governmental instruments, market stimulation has the biggest impact on adoption. The estimation also shows that the adoption of PV panels are price sensitive. This explains the success of the roof-top initiatives where the prices of panels are subsidized. In contrast, high electricity prices in general have no effect on the adoption of all alternative energy sources, but only on those that are most profitable in the respective country.

The main result at this point is that Japan (and Germany) have become front runners in the adoption of PV panels because of preferential subsidies for PV systems by local governments. Taking the factors into account that have led to the adoption of PV energy conversion, two internationalization mechanisms for PV technology are most promising. These mechanisms are the reduction of prices for PV systems and the adoption of policies to support the PV panels by many other governments. Those and other possible mechanisms are discussed in the next sections.

3.2 Price and Cost

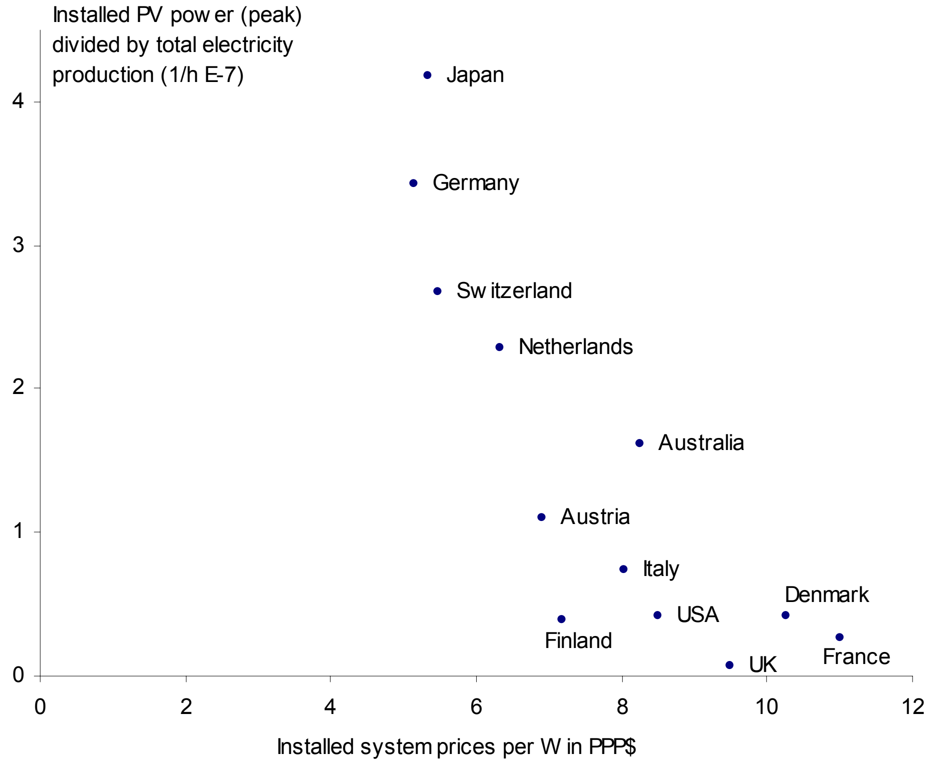
Public subsidies for PV technologies aim to make PV cells an economical alternative as an energy resource. The biggest hope for the sustained adoption of photovoltaic energy conversion in the future without subsidies is the cost reduction effect of large production sizes and learning. If the cost can be reduced to the cost of the production of electricity from fossil resources, PV cells will be internationally adopted. Evidence for the price sensitivity of PV cells is depicted in Figure 4. While the prices for silicon cells are roughly the same worldwide, the prices for systems differ considerably due to pricing-to-market strategies, different competitive situations and market infrastructure. Lower prices for PV systems are associated with higher adoption rates. Lower prices are, therefore, an important success factor of photovoltaic energy conversion. The cost of PV cell production has indeed come down a long way from the beginnings to the present levels of production. Various studies have found that since modules have been industrially produced prices has fallen around 20 % each doubling of the cumulative PV production (e.g. Watanabe et al. 2000, for a review see Harmon 2000 and IEA 2000). These large cost reductions, however, have been mainly achieved by economies of scale, new automated production processes and increases in the efficiency of cells, and not so much through learning, which is defined as cost reductions in the same production unit. This would mean that the learning factor that is used for expectations about future cost reductions is overestimated. Indeed, the IEA finds that in the 1990s prices dropped by between 10 and 17% only (IEA 2003).

Since PV cell cost is still a multiple of electricity by fossil fuels, it is expected that competitiveness in the general energy generation industry will not be reached in the near future. In addition to efficiency increases of fuel combustion generators and turbines the PV industry faces another trend that frustrates its economic sustainability. Although some countries, most prominently Denmark, have introduced energy taxes of electricity in order to increase the price competitiveness of renewable energies, there is no global trend of increasing electricity prices. In most countries electricity tariffs for households decreased during the last 15 years due to increased competition and production cost reductions (Figure 5). The internationalization of PV cells is, therefore, not supported by cost or price trends.

3.3 Demand Trends

In this section, I discuss whether there is a global trend that can spread the demand for PV cells world wide. Yet, the answer is rather pessimistic. Up to now, the adoption of PV energy conversion is accompanied by motivations which vary over time and from country to country. In Japan, the front runner of the adoption of PV cells, a main concern is the dependence of oil imports from Arab nations and the international competitiveness of domestic industries. In contrast, the global warming issue and the reduction of CO_2 became a major motivation for politicians in Europe to turn to solar energy. In the US, however, PV cells are mainly adopted to supply electricity at remote locations and as a backup for unreliable public electricity grids. The biggest market for PV cells is still the off-grid application in households and commercial units such as communication towers and satellites. The regional electricity crises in the US that led to temporary power shortages prompted states to prop up PV support programs. The Department of Energy (DOE) introduced the million roof program in 1997 probably not so much to reduce greenhouse gases but to create a bigger home market in order to strengthen the home base of the US PV industry, which still exports most of its production (see figure 6). Yet, access to and reliability of grids will certainly increase over time. The adoption of PV panels is, therefore, only a reaction to a temporary

Figure 4: PV System Prices and Penetration Rates (2001)



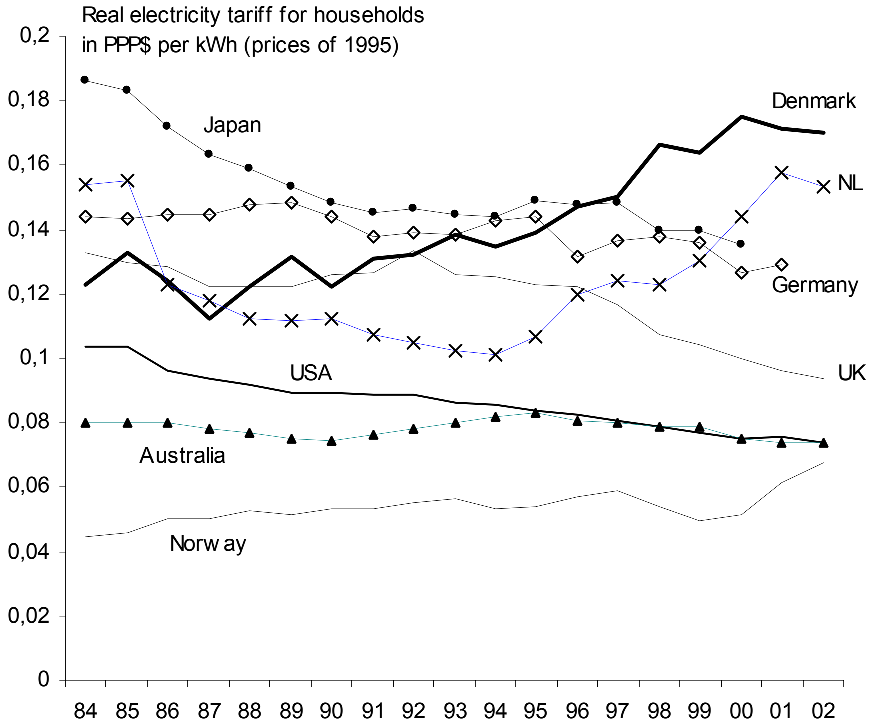
Source: OECD/IEA

problem. And while global warming through CO_2 emissions and the increasing dependency on oil from the Middle East are global phenomena, both are not considered as problematic by all countries. In addition, even if the CO_2 problem gains acceptance, many countries are likely to prefer the adoption of other alternative energy sources to that of PV energy conversion.

3.4 Transfer and Policy Diffusion

A technology can diffuse world wide when its application in a particular country increases the perceived benefit of the technology for other countries as well. This means that either the perception changes, which is called a demonstration effect, or the benefit itself increases. The demonstration effect has been a major reason for the success of the light water nuclear reactor (Cowan 1990). Energy production is normally associated with high investments which translate into high risks. The reliability of a new energy source is therefore an important adoption factor. Yet, the success of PV systems in Japan and Germany merely demonstrated that financial incentives can persuade house owners to invest in small PV units and can even persuade large-scale investors when high feedback rates render electricity produced by PV cells profitable - to erect commercial PV sites. However, neither Japan nor Germany demonstrate that PV energy conversion is economically reasonable or that it increases welfare. This means that only

Figure 5: Electricity Pricing Trends 1984-2002



Source: OECD/IEA

the diffusion of policy support programmes can transfer demand for PV cells abroad.

Policy diffusion is the adoption of the same public regulation or subsidies in many other countries world wide. A related study published in Beise et al. (2002) suggests that the most important internationalization mechanism for environmental innovations is policy diffusion. Developments in the PV industry seem to support this assertion bearing in mind that the mechanisms that internationalized certain electronic innovations - cost reductions and demand trends - are not enough in the case of PV energy conversion.

The most important success factor for the transfer of policies (see Beise et al. 2001) is the demonstration that a policy instrument is effective in solving an environmental problem while at the same time avoiding negative economic side effects. In addition, countries with large markets are often swiftly followed by export-oriented countries in the introduction of innovation-inducing environmental regulation if there is an opportunity to export the regulation-induced innovation. International organizations and international agreements can also spur the internationalization of environmental regulation.Yet, the chances for the international diffusion of policies related to PV energy conversion are rather dim as well. The two biggest problems of PV right now are that all countries do not share the same motives and that PV does not solve an environmental problem. Instead, PV is often a more economical energy source in remote locations.

Within Europe, a major push for alternative energies is the recent directive on renewable energy of the European Union that promotes a doubling of the share of renewable energy by 2010. This directive, which have been adopted by several member states, puts pressure on the governments to promptly implement incentives that can quickly raise the adoption of renewable energies. This spurs the adoption of the instruments that have already been successfully introduced elsewhere, such as in Germany. As a result, German cash incentives for private investments in PV roof-top systems and governmental imposed feed-back rates have been adopted in France and Austria. Grid-connected PV technology has spread throughout most parts of Europe (IEA 2002).

While the policies adopted in Germany and Japan have proven to be nationally successful, the likelihood of the diffusion of these policies world wide is ambiguous. Grid-connection policies are inappropriate for countries where the biggest markets for PV cells are regions with less access to electricity grids. In those countries, policies that support the adoption of non-grid connected PV systems are more suitable. The mixture of policies in Japan has been successful in establishing a market for PV energy conversion. In particular the treatment of PV systems as building equipment matches the tax-incentives for housing popular world wide. However, for an international adoption of a policy beyond Europe and Japan it must be shown that the policies that support the adoption of a new technology such as PV systems are fulfilling the targets of the national policy makers. Yet, those targets are diverse as has been discussed above and PV energy conversion is not a prime candidate for reaching all targets. Another possible scenario for policy diffusion is that the global warming problem becomes so severe that all countries are forced to participate in multilateral efforts to reduce CO_2 emissions. Then, the successful policies on the national level are likely to be adopted internationally. Japan and Germany are the lead markets in this scenario because CO_2 reduction is one of their main motivations. Another external shock that would increase diffusion of PV energy conversion would be a steep increase in the oil price.

While there are international organizations that promote the diffusion of PV cells as an energy source, such as the IEA and Greenpeace, their influence or commitment seems to be small compared to the activism that has led to the substitution of harmful substances, for instance CFCs in sprays or cadmium in paints. While policies are mainly discussed in multilateral conventions, multinational firms can become transfer agents as well. Multinational firms help standardize the roof-top panel design around the world. They transfer products that are successful in their home markets to markets worldwide. Since most of the PV manufacturers are based either in Japan or in Europe, Japanese and European panel designs penetrate the world market much better than US designs. In the US building-integrated and residential roof-integrated PV systems are said to be already mostly of European and Japanese design (Eckart 1999). The biggest manufacturer, Sharp of Japan, has started to built up assembly facilities in the US and plans to do so in Europe to penetrate these overseas markets with its indigenous design. Most manufacturers are diversified large entities and are likely to promote their cell technology and panel designs in other applications within their operations. Anecdotal evidence for this leverage effect of multinational companies includes the fact that BP installs its gas stations worldwide with photovoltaic systems produced by BP Solar.

3.5 Competition

Domestic competition is a characteristic of lead markets. The higher the degree of local competition, the more likely it is to find a superior, economically reasonable application design. Competition would drive down prices, rendering the environmental innovation more price competitive and more intensive marketing activities would attract more users. It is evident that the competition in the Japanese market PV market is the fiercest. The long-time governmental efforts to support a PV industry has led to a diverse group of PV manufacturers and panel assemblers that compete head to head. Evidence for a high degree of competition in Japan is the fluctuation of market shares. Kyocera, Sanyo and Sharp have all obtained the largest market share once. No company ever dominates the market for long. Frequently, new large companies enter the market, bringing with them investment clout and the commitment to effectively compete in the market for a large market share.

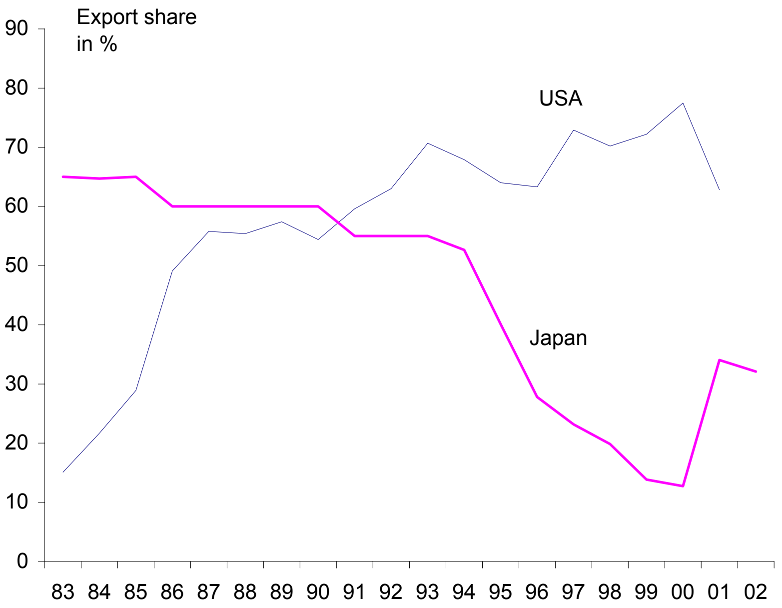
Another indicator for competition are low or continuously decreasing prices. In other countries markets are moving fast as well and new companies enter the market. Continuously decreasing prices indicates the lack of cartels fixing prices. In contrast, in Germany, it is reported that the cost reductions of PV cells are not immediately passed on to buyers through lower prices, indicating a less competitive market structure (Butz 2002). While Germany has attracted many small manufacturers of PV cells and systems, the comparatively small size of the firms can be expected to have a smaller effect on competition because their financial capability in marketing and price competition are very limited.

Porter and van der Linde (1995) suggest that environmental regulation can have a similar effect to competition. It pushes companies to find new innovations in order to satisfy a new environmental obligation such as emission saving or fuel consumption innovations. These innovations might be economically reasonable even for companies that do not have to meet the environmental directive. In the PV case it would mean that the financial incentives to adopt PV systems together with the R&D subsidies could lead to the development of new technologies that would be profitable even without the subsidies. Although the public R&D subsidies for PV technologies aim exactly at this effect - to find materials and compounds that have a sufficiently high degree efficiency accompanied by low costs - the subsidies for the adoption of PV are rather unlikely to accomplish that purpose. The Porter effect assumes that companies are complacent about specific innovation opportunities and are only actively seeking them when research is initiated by regulation. This, however, cannot be said about the photovoltaic industry, in which the innovation target is clear and numerous companies seek solutions to the problems.

3.6 Export

The export orientation of a country in a specific industry adds to its ability to commercialize innovations world wide. A high export orientation of a country means that preferences of foreign markets are included in the design of innovations even if this lowers the attractiveness in the home market. Contrary to other industries, the export orientation of the US producers of PV system is stronger than that of the Japanese and European producers. The US export share of PV cells and modules grew continuously, reaching three quarters in the year 2000 (Figure 6). A reverse trend is observable in

Figure 6: Exports of PV cells and modules from the USA



Source: EIA, JPEA

Japan. The export share of Japan has been declining over time, dropping to around 10 and 30 % (depending strongly on the yen-US-$ exchange rate). As a result of the buoyant market forecasts for Japan in contrast to stagnation in other countries, Japanese companies are focussing more and more on the domestic market.

The main export flows of PV cells and modules are from the US to Germany and Japan. About 50 % of PV exports are shipped to Germany and 11 % to Japan (trade data of 2000, Source EIA). European and Japanese manufacturers develop and manufacture mainly for their domestic markets. The reason for this is that although the United States was the initial lead market, US producers which built up large production capacity had to look abroad when the Federal tax credits expired in 1985 and their home market became sluggish. When Japan and Germany steeply increased the adoption of PV systems, the US production (already acquired by European companies) could deliver quickly. Holian (2000) describes the growing ability of US manufacturers to respond to foreign market preferences, as they "compensate for their distance from many end use markets with a willingness to place technically trained marketing representatives on site around the world." European and Japanese PV manufacturers on the contrary were busy serving the strong market growth in Europe and Japan and did not pursue export markets intensely. Only recently, after the production in Japan started to get saturated have the Japanese and European manufacturers turned to export markets with the building up of sales networks and assembly lines in the US and Europe.

The Japanese and the US government subsidize the adoption of domestic PV systems in developing countries. The German legislature has only recently (2001) introduced improved public export credit insurance for renewable technologies and an export promotion program that mainly intends to provide German renewable energy technology manufacturers with information on export markets. The efforts of governments to spur exports of their domestic producers has not had a big volume effect on their exports yet. Again, the US seems to be more in tune with developing countries' markets, since non-grid-connected applications in rural areas are the main market. Over time US firms established a market strategy based on flexibility and that puts much of the effort on the training of local sales people and customers in rural areas, enabling them to efficiently utilize and maintain a PV system.

4 Conclusions

This paper has discussed the prospect of the international diffusion of photovoltaic energy conversion. The case of PV energy conversion is an illustration of the broader issue of how governments can create lead markets for eco-innovations in order to combine environmental aims with exports. The main political question of the exportability of eco-innovations is: While negative externalities call for governmental regulation, can a country become a lead market by governmental intervention in the market? The question of the international adoption of eco-innovations that have been induced by governmental measures to protect the environment is an important one, because exports of eco-innovations can compensate for the cost disadvantages of the regulation for the local industry. Export chances encourage governments to introduce environmental regulation against the apprehensions of local businesses. While not all policy initiatives for solar energy were introduced to create an export industry, it is an argument often voiced by supporters of PV energy conversion. At least in Japan export chances are one criteria for governmental efforts to create a strong domestic market for PV.

There are several mechanisms that can make a technology internationally successful, despite many differences in preferences and market contexts from country to country. Eco innovations have to overcome the additional obstacle that they are not economically efficient. Innovations in the electronic industry often overcome international differences because of the tremendous cost reductions of mass production. Eco innovations normally do not achieve that level of cost reduction while they would need even bigger cost reduction to persuade users in other countries of adopt them. For eco-innovations the most import condition for international diffusion is therefore that they be environmentally efficient and that there be a global environmental problem they help solve. This is the basis for the global diffusion of eco-innovations. Environmental efficiency, the ability to solve environmental problems effectively and economically in a way that the costs are not higher than the negative effects of the environmental problem, is the starting point for global policy diffusion. The second condition is that the technological design favored by the policies is compatible with foreign markets, that the same design can be adapted in the follower markets. This aspect of design incompatibilities and design mismatch has not received much attention with policy makers yet, because of the too optimistic expectations that the experience and success of one design can be easily transferred by the domestically successful manufacturers to other designs that are appropriate for foreign markets.

Generous subsidies in Japan and Germany have succeeded in creating a local dynamic market for PV systems and promoting the global breakthrough of PV systems as well. A closer look, however, shows that the prospect of a world market for photovoltaic energy conversion is rather bleak. Judging by the internationalization mechanisms that have made a technology internationally successful, the success of PV technology in Japan and Germany does not seem likely to render its global success soon.

The shortcomings of the domestic policies in Japan and Germany in starting an international bandwagon in the PV industry are that they focus on the cost reduction potential as the main internationalization mechanism, while policy diffusion seems more important. PV energy conversion needs governmental subsidies to remain economical for a long time. The expected cost reduction that can be achieved by mass production in Japan is still not sufficient to render PV an economical alternative to traditional energy resources. In contrast, examples of globally successful eco-innovations have shown that global policy diffusion is a more effective internationalization mechanism. If a policy instrument diffuses internationally, so does the innovation design responding to the policy instrument, thus raising the prospect of exports by the country that first introduced the policy. In the case of PV energy conversion, policy diffusion went only half way in few industrialized countries. Any further policy diffusion that would create a market similar to the one in Japan cannot be expected, because other countries would receive little economic benefit from adopting PV. In this case, the effectiveness of a policy instrument in combatting environmental problems is the most important success factor for the international diffusion of this policy instrument. Yet, the policies in the PV case are not successful in environmental terms. PV cells are efficient in supplying electricity for remote applications, where a grid-connection would be more costly. PV systems are rather inappropriate for helping to solve the main environmental problems created by exhaustible energy conversion such as CO_2 emissions in countries where PV energy conversion has been "successfully" applied. The production of PV cells itself is energy intensive. A mass production of PV cells, therefore, increases energy consumption for years until a large stock of PV applications can start lowering total consumption of depletable resources. In addition, policies that have worked well in Europe are not applicable in other countries. Feed back rates are limited to grid connected markets. Non-grid-connected markets need other instruments. Yet, in the foreseeable future the only market for PV without subsidies is the non-grid market. PV energy conversion could help electrify developing countries. The problem with this scenario is that PV systems are more expensive than diesel generators and that the main target market is shrinking in the long run since more and more regions get access to a regional or national grid that is fed mostly by large central power generators.

When international policy diffusion is not achievable, then the United States remains the test bed for solar energy, where the fate of PV will be answered. With the energy production cost of solar cells unlikely to come close to that of conventionally generated electricity in the foreseeable future and the non-grid market the main economically feasible market, the US offers the conditions of a lead market and the leverage effects (size, competition, export orientation) to make it an international success. Thus, despite the efforts of Japan and Germany to create a local lead market, it seems that their measures will not be able to change the role of the United States as a test market. Only if PV experiences a breakthrough there can it develop as a global innovation.

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