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# Transforming the energy system - the evolution of the German technological system for solar cells*

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## 1. Introduction

It is widely recognised that, for environmental and in particular climate reasons, the energy sector needs a ‘creative destruction,’ in which renewable energy technologies replace those using fossil fuels. A transformation of the energy sector requires the emergence and growth of new technological systems (Carlsson and Stankiewicz, 1991; Jacobsson and Johnson, 2000) based on a range of renewable energy technologies, such as wind turbines, solar collectors, biomass-based combined heat and power plants and solar cells.

We cannot expect a transformation to be achieved without government support for the new technologies as they attempt to challenge technologies that have had decades to mature. As the cases of natural gas and nuclear power demonstrate, support may be needed not just for years but for decades (Watson, 1997, Norberg-Bohm, 2000, Goldberg, 2000). In particular, we expect that government support for the new technologies will come in realigning the institutional framework so that it favours the emergence of new technological systems. Substituting established technologies implies, however, that new interest groups will challenge existing ones, and a realignment of the institutional framework, and a transformation of the energy system, cannot be expected to be achieved without overcoming considerable opposition from vested interests involved with the incumbent technologies.

The policy challenge is considerable and is made even more daunting since we do not have adequate knowledge of other features of the transformation process and, therefore, we cannot inform policy makers attempting to manage the process. The purpose of this paper is, therefore, to improve our understanding of processes involved in the formation and growth of new technological systems in the energy sector and to identify the associated key challenges for policy makers managing the transformation process. We will do so by examining the development of the German technological system for *solar cells* over the past twenty-five years.[1] This is a technology that generates electricity directly from solar irradiation. Although it is

[1] This follows on a study of wind turbines where the case of Germany was contrasted with those of Holland and Sweden (Johnson and Jacobsson, 2002).

currently an insignificant technology in terms of its contribution to the power balance, it is currently being rapidly diffused and it has a very considerable potential. We have chosen to analyse the case of Germany since it has been a leading country both in terms of the allocation of funds to Research, Development and Demonstration (RDD) and, lately, in terms of the diffusion of solar cells.

The structure of the paper is as follows. In the next section we outline our analytical framework. We use a 'technological system' approach in which we will trace the evolution of the system that has a bearing on the generation and diffusion of solar cells. Section three provides an overview of the technological and market developments in solar cells. We will point to high expectations for solar cells and, until recently, a slow diffusion. We will also point to the existence of a range of competing design approaches. In section four, we analyse the evolution of the technological system for solar cells in Germany. An initial preparatory stage lasted until about 1989 and was mainly characterised by knowledge build up induced by a Federal RDD programme. This was followed by a second stage characterised by political struggle over the regulatory framework and the subsequent beginning of a virtuous circle for solar cells. Section five contains conclusions and a discussion of a set of policy challenges. We emphasise the following points: (1) the role of a coalition of system builders which successfully influenced the regulatory framework so that markets could be formed: (2) the length of the learning period and the large number of actors which need to learn; (3) the importance of policies which form early markets (not only early niche markets, but beyond those) as only markets may induce firms to enter and learn, and (4) the need to run market formation policies simultaneous to policies which maintain technological variety.

## 2. Analytical framework

As is argued in the broader literature on innovation systems, the innovation and diffusion process is both an individual and collective act. The determinants of this process are not only found within individual firms; firms are embedded in innovation systems that aid and constrain the individual actors within them. The process whereby a specific new technology emerges, is improved and diffuses in society may be studied using the concept of a technological system (Carlsson, 1995, 1997; Jacobsson and Johnson, 2000). This entails using a technology-specific innovation system approach and rests on the assumption that there are many technological systems in a country and that these vary in their ability to develop and diffuse new technology. The technology-specific features of the approach make it particularly attractive when the focus of the enquiry is on the competition between emerging technologies and incumbent technologies (and between the associated technological systems).

A technological system is defined as a "…network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure… and involved in the generation, diffusion, and utilization of technology." (Carlsson and Stankiewicz (1991, p. 111).

The approach suggests that the emergence of new technologies does not take place in a vacuum but rather through the interplay between firms and other organizations, such as universities, industrial associations and government bodies and that this process is greatly influenced by the institutional framework.[2]

A technological system is made up of three main elements:[3]
*Actors and their competences*, technical and others. These may be firms or other organisations. A particularly important set of actors is 'prime movers' or system builders (Hughes, 1983). These are firms, or other actors, which are technically, financially and/or politically so powerful that they can strongly influence the development and diffusion process. Other notable ones are non-commercial organisations acting as proponents of a specific technology (ies). Unruh underlines the existence of a range of such organisations and the multitude of roles they play (2000, p. 823):

"Private, often non-commercial institutions tend to emerge because users and professionals operating within a growing technological system can, over time, come to recognize collective interests and needs that can be fulfilled through establishment of technical… and professional organisations…These institutions create non-market

[2] Technological systems are, of course, not static but inherently dynamic and unstable. The dynamics can be viewed as a function of a tension between the logic of technology and the nature of actors, networks and institutions. Any change in a component in the system may trigger a set of actions and reactions that relieve the tension and propel the system forward. The boundaries, in terms of both actors and knowledge, may consequently alter, sometimes quite rapidly (Carlsson et al., 2002).
[3] This paragraph and the following two, draw heavily on Johnson and Jacobson, 2002.

forces…through coalition building, voluntary associations and the emergence of societal norms and customs. Beyond their influence on expectations and confidence, they can further create powerful political forces to lobby on behalf of a given technological system"

*Networks* constitute important channels for the transfer of both tacit and explicit knowledge. These networks may be built around markets and may therefore be conducive to the identification of problems and the development of new technical solutions. They may also be non-market related and conducive to a more general diffusion of information. Being strongly integrated into a network increases the resource base of individual firms and other organisations, since it gives access to information and knowledge of other actors. The network also influences the perception of what is desirable and possible, i.e. it shapes our images of the future, which then guide specific decisions, be they in firms or in other organisations.

*Institutions* stipulate the norms and rules regulating interactions between actors (Edquist and Johnson, 1997) and the value base of various segments in society. The roles of institutions vary: some influence connectivity in the system whereas others influence the incentive structure or the structure of demand. As is emphasised in institutional economics (e.g. Edquist and Johnson, 1997), and in the literature on innovation systems (e.g. Carlsson and Stankiewicz, 1991, Porter, 1998), institutions are important not only for the specific path a technology takes but also to the growth of new clusters.

Central to a process whereby a new technological system emerges and grows, is the entry of firms into various points in the value chain. On the one hand, this involves enlargement of an initially small technological system, whereby new firms fill 'gaps' or meet novel demands in the evolution of the system. Each new entrant brings knowledge and other resources into the industry and begins, through a learning process, to function within the new technological system. On the other hand, as has been noted by many authors (e.g. Smith, 1776; Young, 1928), it involves the formation of a division of labour and, associated with this a further learning stimulated by specialisation and accumulated experience.[4]

[4] As noted above, the enlargement of a technological system involves the 'entry' of organisations other than firms too. It may involve Universities, of course, but also organisations, which promote the new

However, there are many reasons for expecting that the selection environment is biased in favour of incumbent technological systems and that, consequently, a new technological system may fail to develop or may only develop very slowly[5] (Carlsson and Jacobsson, 1997; Jacobsson and Johnson, 2000). For instance:[6]

- Institutions may fail to align themselves to the needs of the new technology – this may encompass the regulatory framework or the functioning of the educational and capital markets.

- Markets may not be formed due to, for instance, the phenomenon of increasing returns, which benefits the incumbent, well established technologies. The non-formation of markets may also be due to buyers and sellers not being aware of each other's needs; to turn need into a well-articulated demand that can be met by suppliers requires information exchange between the two sides.

- Firms may not enter due to a lack of markets or because they tend to build on their existing knowledge base when they search for new opportunities, which may restrict their search process.

- A network can fail to aid the new technology simply because of poor connectivity between the actors. The proponents of the new technology may also be organisationally too weak to counteract the influence on legislation, public opinion etc. of the vested interest groups of the incumbent technology.

A useful way to analyse the dynamics of a technological system, or the lack of it, is to focus on how a number of *functions* are performed (Johnson and Jacobsson, 2002, Rickne, 2000). These functions constitute an intermediate level between the components of a technological system and the performance of the system. An extensive review of the innovation system literature, (Bergek, 2002; Johnson and Jacobsson, 2002) suggests that there are five basic functions that need to be performed in a technological system:[7]

- The creation of *'new' knowledge*, being an integral part of innovations and which leads to an increase of alternatives in the system
- Influencing *the direction of search processes* among users and suppliers of technology. This function includes guidance with respect to the growth potential of a new technology, which may be closely linked to the legitimacy of it, and guidance in relation to choice of specific design approach.

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technology in various ways. These may be industry associations but also other organisations, such as various types of pressure groups organised by members of the public (e.g. Greenpeace).

[5] Johnson and Jacobsson (2002) elaborate on various types of 'blocking mechanisms'. See also Unruh (2000) for an extensive review of mechanisms locking us into a carbon economy and Walker (2000) for a case study on entrapment in a large technological system.

[6] This is based on Jacobsson and Johnson (2000).

[7] Rickne (2000) provides us with a more detailed set of functions.

- *The supply of resources* of both a general nature such as capital, competence and input materials.
- *The creation of positive external economies*, which is a pivotal characteristic of a functioning technological system. An example is the formation of buyer-seller linkages or networks that provide ‘spill-over’ effects by the reduction of uncertainty, guiding the search process, reducing the cost of information, accessing tacit knowledge and sharing of costs.
- *The formation of markets* since innovations rarely find ready-made markets instead these need to be stimulated or even created. This process may be affected by firms’ marketing efforts and also by governmental actions to clear legislative obstacles and by various organisations’ measures to legitimise the technology.

These functions are not, of course, independent of one another and a change in one function may lead to changes in others (Johnson and Jacobsson, 2002). For instance, the creation of an initial market may act as an inducement mechanism for new entrants that bring new resources to the industry. The linkages between functions may also be circular, setting in motion a virtuous circle, or a process of cumulative causation (Myrdal, 1957). Indeed, as pointed out long ago by Myrdal, these virtuous circles are central to a development process - as these circles are formed, the evolution of the technological system becomes self-sustained. He even suggested that “ the main scientific task is…to analyse the causal inter-relations within the system itself as it moves under the influence of outside pushes and pulls and the momentum of its own internal processes” (Myrdal, 1957, p. 18).

There are two main reasons for analysing dynamics in functional terms as well as in terms of each component of the technological system. First, we can define the border of the system, an inherently very difficult task (Carlsson et al. 2002), by analysing what promotes or hinders the development of these functions (Johnson and Jacobsson, 2002). Second, there is no reason to expect that a particular configuration of a technological system, or structure, is related to the performance of the system in a clear and unambiguous way. By arranging our empirical material in terms of functions, we can trace the way through which a particular entry/exit pattern, actor combination or a specific institutional set-up[8] shapes the generation, diffusion and utilisation of new technology.

[8] Take, for instance, the current debate over which policy structure is the most appropriate to promote renewable energy, where the proponents of Green Certificates advocate that this is a superior policy instrument compared to using fixed prices and privileged access to the market (as practised in Germany, see Jacobsson, 2002).

In summary, we have a framework that not only provides us with a tool for analysing the dynamics of a technological system through capturing *how* the functional pattern of an innovation system evolves, but also the extent to which *virtuous circles* exist and what *factors and actors shape* the process.

## 3. The market for solar cells and its various competing designs

This section briefly describes the development of the global market for solar cells and traces a set of changes in the technology.

### 3.1 Market development – bold visions but only niche markets

Given the small size and modular nature of solar cells, these have a range of potential applications. One of these is to supply electricity to the grid as conventional power technologies. The presently high costs of power generated by solar cells (see below) means that the diffusion of solar cells to this application has to be supported by very generous policies. There are, however, a large number of off-grid applications where the high cost is of less relevance. Examples of such applications are powering watches, satellites, parking meters, summer homes in Scandinavia or villages in Tanzania. In such applications, the sales of solar cells can be made on commercial terms.

The history of the diffusion of solar cells can be described in terms of five periods, where the emphasis has shifted between policy driven markets and commercial ones, see Figure 3.1.

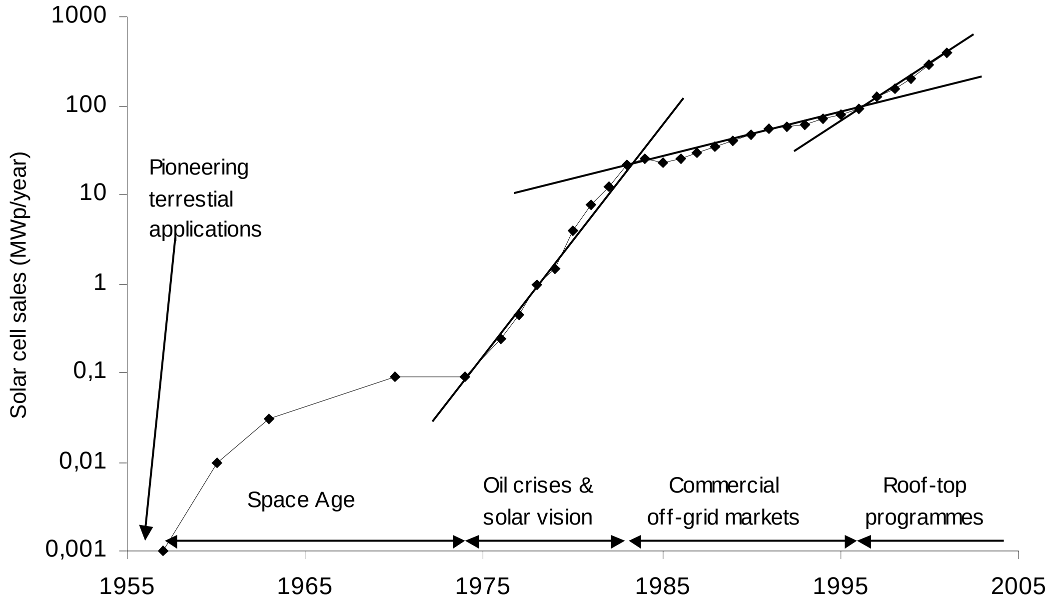


Figure 3.1 Five phases of solar cell diffusion

Sources: Wolf 1974; Prince and Barrett 1982; Maycock 1996, 2000; PV News various issues

The first solar cell was invented nearly fifty years ago (in 1954) by Bell laboratories and inspired by successful commercialisation of other semiconductor devices, two companies started to produce solar cells. A number of pioneering applications were tried, from toys to stand-alone power supply in remote places but sales remained extremely small (Wolf 1974).

However, an unexpected market emerged when the Vanguard I satellite,[9] launched in 1958, proved to be a success using solar cells as power source. The satellite market became the first significant commercial market and annual production rose to about 0.1 MWp per year in the late 1960s (Figure 3.1).

In the early 1970s, in the wake of the first oil crisis and in a time of growing environmental awareness, a greater interest in solar cells for power production emerged. At the opening session of the International Conference on Photovoltaic Power Generation in 1974, Boiko (1974) suggested that:

[9] The project was under US Navy management and under the monitorship of the Department of Defence which, again, point to the role of the military in the process of emergence of new technologies.

” in the years to come, the use of photovoltaic power will know an enormous extension. In less than ten years from now, the economic situation of solar power will be such that it might compete with almost all other classical power sources.”

Government Research, Development and Demonstration (RDD) programmes emerged in many countries, most notably in the USA but also in Japan and Germany, see Figure 3.2.

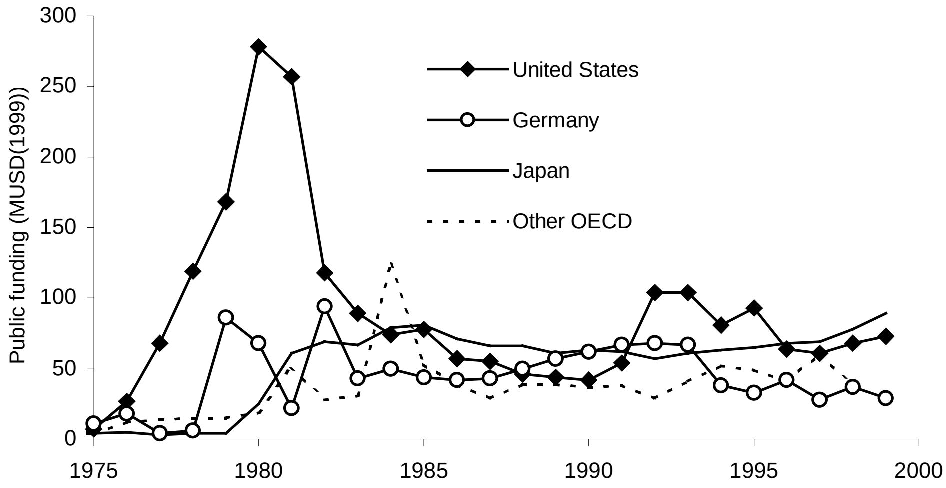


Figure 3.2 Public solar cell research, development and demonstration funding in OECD, 1975-1999 (in million 1999 USD)

Source: Elaboration on IEA, 2001,b

Against the background of the second oil crisis and a rapid increase in solar cell production, bold visions of a quick transition to a solar cell powered world were made. Macomber (1980), for instance, extrapolated the market growth trend on the basis of the growth between 1974 and 1980 (about 85 per cent) and forecasted a cumulative installed solar cell power of 870 $GW_p$ in the year 2000.

Annual production reached 22 MWp in 1983. The bulk of this growth was tax-credit financed *large-scale grid-connected plants* in California, (Maycock 1986). However, the era of large-scale solar cell plants ended with changes in the RDD and tax policies made by the Reagan administration. A market contraction in the US was somewhat balanced by developments in other parts of the world, in particular by the increasing numbers of solar cells produced in Japan for *consumer electronics products*. But the era of unlimited solar optimism was over. In the period from 1983 to 1996 the market grew on average by only 13 per cent per year. The consumer product segment grew initially but it was the commercial *off-grid power markets*, much of it in developing countries that dominated the period.

A new growth phase began in 1997. The trend break was not due to any technological breakthrough but to ambitious market formation programmes in developed countries. In December 1994, the Japanese government announced a national policy which became known as the 70 000 roofs programme. Various forms of investment subsidies were given for *rooftop mounted grid-connected systems.* From 1997, the programme expanded rapidly, and Germany followed with its own support programmes. Largely as a consequence of these programmes, solar cell production grew by as much as 35 per cent per annum from 1997 to reach 401 $MW_p$ in 2001.[10]

The stock of solar cells reached about 1.7 $GW_p$ in 2001,[11] a far cry from the vision of 870 $GW_p$ by Macomber (1980). The supply of electricity is a mere 2.5 $TW_h$ which is about half of the output of one nuclear power station.[12] Yet, the growth rates have been impressive since 1997 and new visions of a solar cell powered future have been formed (Greenpeace and EPIA, 2001).

### 3.2 Technological development – distant cost targets, and dominance of silicon cells

The solar cell invented by Bell Telephone Laboratories was a *crystalline silicon solar cell* with an efficiency of 6 per cent, i.e. 6 per cent of the incoming energy of the sun (insolation) was transformed into electricity.[13] Since then, this design approach has dominated the market.

[10] The share of the grid connected market segment grew to over 50 per cent in 2000 (EPIA 1995, IEA 2000).
[11] We used the data in Bergek (2002), table 2.1 which applied to the year 2000 and added the production for 2001.
[12] In contrast, the electricity supply from wind turbines, another 'new' renewable energy technology, was about 40 $TW_h$ in 2000 (Bergek, 2002), table 2.1.
[13] At this point Edmund Becquerel's discovery of the photovoltaic effect, light induced voltage and current, was already 115 years old.

Prices of silicon modules (a number of cells are combined into a module), which had been several hundred USD/Wp[14] in the early 1960s, dropped to below 20 USD/Wp in the 1970s, see Figure 3.3. In the early 1970s, the goal of the US photovoltaics research programme was to reach 0.5 USD/Wp by the mid 1980s (Herwig 1974).

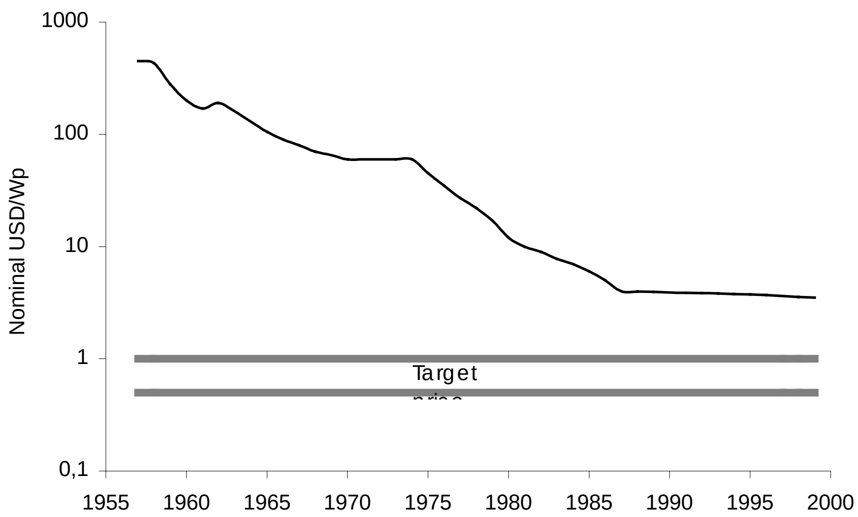


Figure 3.3 Solar cell price set in relation to target price

Sources: Wolf 1974; Prince and Barrett 1982; EPIA 1995; Maycock 1996, 2000

However, by 1980, when prices had not gone below 10 USD/Wp, the search for new materials, which had been going on for some time, was intensified (Kazmerski, 1997). Several competing design approaches were researched, and all of these as well as the dominant silicon cell continuously improved their performance in terms of efficiency, see Figure 3.4.

[14] PV prices are normally given as USD per watt of peak power ($W_P$), which is defined as the electricity power output at an insolation of 1000 W/m$^2$ (approximately the maximum insolation at the Earth's surface).

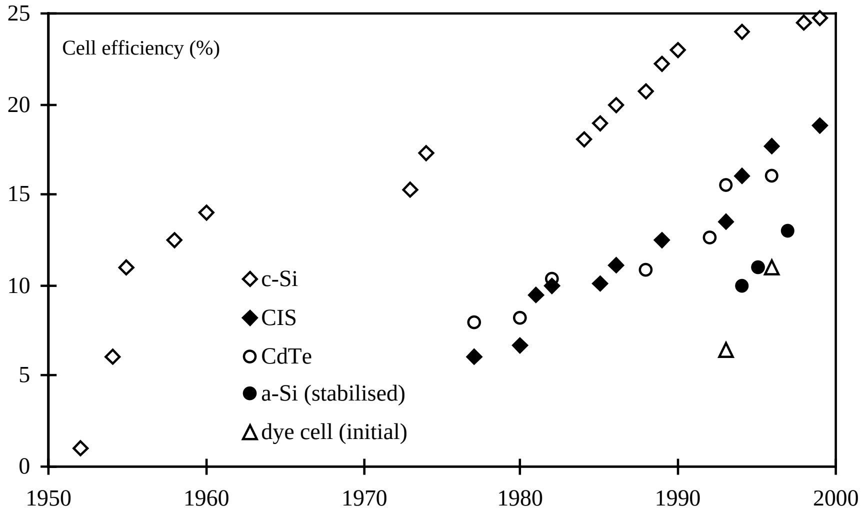


Figure 3.4 Record one-of-a-kind laboratory cell* efficiencies for five competing designs

* The abbreviations stand for different design approaches: c-Si (crystalline silicon cells); CIS (copper indium diselenide); CdTe (cadmium telluride; a-Si (amorphous silicon)

Sources: Green et al. 1999; Shah et al. 1999; Zweibel 1995; Zweibel et al., 1996

In 1954 came the first publication on *cuprous sulphide/cadmium sulphide ($Cu_2S/CdS$)* thin-film solar cells (Kazmerski 1997). In the 1960s, development of this technology was directed at space applications, and at terrestrial applications in the 1970s. Professor Boiko of Unesco (1974) then argued, "It is undeniable that these solar-cells are the most serious competitor with silicon solar cells." Pilot production lines were installed in the USA and in Germany but work on $Cu_2S/CdS$ ceased in the mid 1980s due to their electrochemical instability (Schock and Pfisterer 2001).

Work on *cadmium telluride (CdTe)* started in the early 1960s and research on *amorphous silicon (a-Si)* and *copper indium diselenide (CIS)* was initiated in the mid 1970s (Schock and Pfisterer 2001). In 1980, Sanyo marketed the first pocket calculator powered by a-Si solar cells, which marked the starting point of a rapid exploitation of the consumer electronics segment.[15] The success in this niche market, and the potentially very low material costs of this design approach, shifted the hopes

[15] The advantage of thin films in this segment is due to the flexibility regarding shape, size and the number of cells within a module and can, therefore easily be adapted to the requirements of different products.

for a low cost solution to a-Si. Substantial investments in research and development were made. For instance, EU shifted the focus of its funding to thin films, mainly aSi, in 1985 (Palz and Kaut 1985) and in the same year Maycock (1985) commented on a target to reach 2 USD/Wp that ”we now see amorphous silicon …with the highest probability of reaching these goals.” However, to date, the growth in a-Si module production has not been sustained compared to that of crystalline silicon; although a-Si module shipments increased from 13.7 MW/year in 1991 to 27.0 MW/year in 2000, their share of the world market fell.

In the 1990s, the RDD policy of the larger nations learned from their earlier mistakes and emphasised greater diversity. For example, in a presentation of the US solar cell programme plan for 1991-1995 Annan and Rannels (1991) stressed that there ”is no known reliable method that will tell us which materials, which device design, or which system potentially will be most effective in meeting our mission. Therefore, the National Photovoltaics Program supports research and development in several different technologies”. In 2002, CdTe and CIS solar cells are produced on pilot lines, new larger-scale production plants of a-Si are planned, and new competing designs, such as microcrystalline silicon, thin-film crystalline silicon and dye-sensitised cells, attract attention and funding.

In sum, bold visions of market development and the diffusion of specific design approaches have been replaced by the exploitation of market niches and the continued dominance of silicon solar cells. After decades of substantial cost reductions, the cost targets are still distant. Yet, recent major policy interventions in the form of market formation programmes have resulted in a rapid growth in the market, an increase in the number of competing designs and a new optimism.

## 4. The evolution of the German technological system for solar cells

We will divide the development of the German technological system for solar cells into two phases, the first ending in 1989 and the second from 1989 to 2001. The first period was primarily characterised by the dominance of the function ‘supply resources’ in the form of the build up of a large Federal RDD programme. This included the start of a demonstration programme that began to generate knowledge about the application of solar cells. In the second phase, the system was greatly enlarged, the functions were much strengthened and virtuous circles began to be formed.

### 4.1 The period of ‘science based experimentation’ – a preparatory phase

In the mid-1960s, the US placed export restrictions on the European Space Agency. In response to this, Telefunken and Siemens started to develop solar cells. These were first crystalline silicon cells but later both Telefunken and the Battelle Institute began to experiment with cadmium-based thin film solutions (Bonnet, 2000). The US embargo was later lifted and a real surge in interest in solar cell technology did not come until the two oil crises in the 1970s. At this time, a strong Green movement had emerged, a movement, which saw neither nuclear power nor oil as long term solutions (Jannsen, 2000).

As was seen in Figure 3.2, the Federal government responded to this movement by increasing its expenditure on solar cell RDD. From 1978, RDD in the field of solar cells has been financed on a scale, which has been consistently high,[16] both in absolute and relative terms as compared to other countries’ efforts in solar cell RDD.[17]

In the period 1977-89, 18 universities, 39 firms and 12 research institutes received Federal funding in this field.[18] As a consequence, a broad academic cum industrial knowledge base began to be built up about twenty-five years ago. RDD funds were allocated to the exploration of a whole range of issues connected to the application of solar cells, such as the development of inverters. However, the major part of the

[16] In general, in comparison with RDD spent on nuclear technology, money spent on RDD for renewables is very small.
[17] Germany became the second largest spender on RDD in absolute terms (after the US) in 1978 and since then Germany has been ranked number 2 or 3 (after the US and Japan). In terms of RDD expenditure per capita, Germany has either been the highest or the second highest spender (IEA 2001b).
[18] These are estimates based on elaboration of data from Jahresbericht Energieforschung und Energietechnologien, various issues, Bundesministerium für Wirtschaft und Technologie.

research funding was directed towards cell and module development and the prime focus was on crystalline silicon cells.[19]

Throughout the period, funds were also given to research on several thin-film technologies. Amorphous silicon (aSi) was then regarded to be the thin-film technology that would eventually replace crystalline cells (section 3.2) and the bulk of the resources to thin-film research were channelled towards that technology. Around 1980, the former Messerschmidt-Bölkow-Blohm company (MBB) began experimenting with aSi, aiming at space applications (Bonnet, 2000). At the end of the 1980s, they built a dedicated plant in the belief that aSi would become a base material for cost-effective solar modules (Maurus and Schade, 2001).

Research was also fostered in several other design approaches; copper sulphide, cadmium selenide, cadmium telluride and copper indium diselenide (CIS). For instance, NUKEM (a supplier of nuclear elements) diversified into cadmium sulphide cells using its knowledge of heavy elements chemistry.[20]

Hence, the ‘supply of resources’ in the form of Federal RDD funding induced a ‘creation of knowledge’ in many alternative directions and a few firms were ‘guided in their search process’ to enter into solar cell development.

[19] In the reports on German RDD funding, crystalline, thin-film crystalline and amorphous silicon have separate classification codes, while other technologies share one code. We have allocated projects to a number of other technologies (e.g. CdTe and CIGS) by scrutinizing project descriptions.

[20] Due to environmental problems associated with the use of cadmium, they later considered other thin-film technologies, e.g. a-Si , but then concentrated on crystalline silicon solar cells (Hoffmann, 2001).

**Table 4.1 Diffusion of solar cells in Germany, in $MW_p$***

| Year | Flow ($MW_p$/year) | Stock ($MW_p$)** |
|---|---|---|
| 1983 | 0.30 | 0.3 |
| 1984 | 0.00 | 0.3 |
| 1985 | 0.00 | 0.3 |
| 1986 | 0.00 | 0.3 |
| 1987 | 0.00 | 0.3 |
| 1988 | 0.66 | 1.0 |
| 1989 | 0.00 | 1.0 |
| 1990 | 0.59 | 1.5 |
| 1991 | 1.01 | 2.5 |
| 1992 | 3.10 | 5.6 |
| 1993 | 3.28 | 8.9 |
| 1994 | 3.54 | 12.4 |
| 1995 | 5.35 | 17.8 |
| 1996 | 10.10 | 27.9 |
| 1997 | 14.00 | 41.9 |
| 1998 | 12.01 | 53.9 |
| 1999 | 15.60 | 69.5 |
| 2000 | 44.30 | 113.8 |
| 2001 | 65.00 | 173.8 |

Sources: 1983-1989: EPIA (1985); 1990-1992: DFS (2000); 1993-2000: IEA (2001a); 2001: Schmela (2002)

*For the period 1983-1989 only large and medium size solar cell power plants are included, but the residual appears to be insignificant.
** No degradation is accounted for and we assume that no installations have been scrapped

The year 1983 saw the first German demonstration project. This was wholly financed by the Federal Government and used cells from the German firm AEG (formerly Telefunken, Goetzberger, 2000). The plant had an effect of 300 $kW_p$ and was the largest in Europe at that time. In 1986, it was followed by a demonstration programme, which by the mid-1990s had contributed to building more than 70 larger plants for different applications. All of these were accompanied by a two-year monitoring programme (IEA, 1997,1999).

By 1990, the accumulated stock amounted, however, to only 1.5 $MW_p$ (see table 4.1). Although the demonstration programme had a minor effect in terms of ‘facilitating market formation’, it was effective as a means of ‘creating application knowledge’.

The objective of building these plants was not only to demonstrate the new technology but also to learn more about solar cells, evaluate them as a future option as well as to 'create new knowledge' about how to apply solar cells. For instance, one of the demonstration plants, the first one built by a utility, not only evaluated 15-20 different modules but it also tested how to integrate a plant of that size (340 $kW_p$) into the landscape (Mades, 2001).

Another utility, Bayernwerk, built its first plant (320 $kW_p$) in 1989 in collaboration with Siemens and BMW. The objective of this plant was to employ solar cells to generate hydrogen that was to be used in combination with fuel cells (Schiebelsberger, 2001). Following this collaboration, Bayernwerk and Siemens founded Siemens Solar, which subsequently became one of the largest firms in the global industry. Siemens Solar also bought the US firm ARCO in order to get into the larger US market and to get access to both a-Si and CIS technology.[21]

The period also saw the formation of three types of organisations promoting renewable energy. The first type is a broadly based organisation which includes members of the public. One example[22] is the German Society for Solar Energy **(**DGS), It was started in 1975 and has 3 600 members. DGS has set up special groups consisting of both scientists and industry representatives dealing with various themes, for instance biomass and solar cells. The groups' objective is to diffuse information to politicians and industry. A presidium undertakes most of the discussions with policy makers and DGS is present on the advisory groups on energy within the different political parties (Jannsen, 2000). Position papers on various subjects are written by DGS or together with other organisations and submitted to these Advisory Groups (Jannsen, 2000). A second organisation of this type is Förderverein Solarenergie with 2 000 members. It was started in 1986 and in 1989 it developed the concept of 'cost covering payment' for electricity generated by renewable energy technology, a concept, which was later applied in various feed-in laws at Federal and local levels.

[21] It also meant that Siemens later terminated its cell manufacturing in Germany after pilot plant level (Schiebelsberger, 2001).
[22] The list is not exhaustive as there are a multitude of such organisations in Germany.

A second type of organisation is the conventional industry association. In 1978, the German Solar Energy Industries Association was founded (Bundesverband, 2000). By 1980, there were about 35 members. The work of the association was initially focussed on diffusing information of a more technical nature regarding the use of solar technology, but in the 1980s it was increasingly orienting its work towards influencing members of the German parliament (Bundesverband, 2000). A second industry association, the German Professional Association of Solar Energy was founded in 1979.

A third type of organisation is Eurosolar, which was started in 1988. This is an organisation for campaigning *within* the political structure in contrast to the conventional pressure groups that lobby politicians. Eurosolar has 65 members from all political parties within the German Parliament, excluding Liberals, and 800 politicians at all levels in Germany (Federal, Ländern, local). From the start, the focus of the work was to create an awareness of the potential of renewable energy technology amongst the public and politicians. Later, specific policies were designed and promoted in the political process (Scheer, 2001).

The function of these organisations is to promote solar and other renewable energy technology by trying to generate institutional change. The work of the associations has, in part, been of a technical nature, such as promoting the formation of standards. More importantly, it has been directed towards changing perceptions of what is possible and desirable in terms of solar energy amongst policy makers, industry and the public. It has also shaped the design of specific policies for solar energy at Federal, Ländern and local levels (Scheer, 2001).

Of course, the formation of these organisations implied the building up of networks. These networks operate within each organisation, across them, between the first two types of organisations and policy makers and, finally, between policy makers (Eurosolar). The ground was laid for a ‘creation of positive external economies’ primarily through a process of highly organised work to change the institutional set-up in favour of solar technology, the benefits of which can be seen in the following period.

In sum, in this first, and preparatory period, the dominating function was the ‘supply of resources’ in the form of both Federal RDD programmes. This ‘guided the direction of search’ into solar cells and ‘created new knowledge’ about a range of technological alternatives, and about the application of these, in a large number of organisations. However, no virtuous circles could be identified; the process of development of the technological system was not self-sustained.

### 4.2 Towards a self-sustained growth of the technological system (1990-2001)

In the second phase, the technological system began to evolve into a more self-sustained one, but only after a political struggle to change the regulatory framework for the energy sector. The Federal RDD policy continued to ‘supply resources’, see Figure 3.2, and ‘guided the direction of search’ into solar cells. Indeed, even more firms and other organisations began to experiment with solar cells. In the period 1990 to 1999, an additional 15 universities, 41 firms and 17 research institutes received Federal RDD funding. Crystalline silicon cells still dominated the research but funding continued to be given to thin-film technologies too. By the mid 1990s, a pattern had evolved where four thin-film technologies received broadly the same amount of funds. Hence, a search was guided into many technological alternatives with a subsequent broad knowledge formation ‘upstream’.[23]

In 1990, a demonstration cum ‘market formation’ programme of small solar cell installations, the 1000 roofs programme, was started. Eventually, the programme led to the installation of more than 2 200 grid-connected roof-mounted installations with an effect of 5.3 $MW_p$ in the first half of the 1990s (IEA, 1999**)**. The origin of this programme was a Parliamentary resolution calling for more RDD in renewables in 1988 (Scheer, 2001). This resolution should be seen against the background of the Chernobyl accident in 1986, which was followed by a Congress where SPD decided to dismantle nuclear power (Eichert, 2001). The German Ministry of Research responded not only with a 250 MW programme for wind energy (see Johnson and Jacobsson, 2002) but also with this solar cell programme.

[23] In addition to the Federal Programme, initiatives at the state levels increased the level of experimentation. For instance, a new applied R&D institute, INAP, was founded in Gelsenkirchen by

It was an experimental programme, which was followed by measurement and analysis of the performance of the various installations. One of the most important objectives was to develop installation know-how and a standard for installing the systems (Fraunhofer, n.d.). Internationally, this programme was seen as very advanced – it was the most extensive test in the world for photovoltaic systems (Fraunhofer, n.d). It led to the development of new inverters, an entry by a large number of electrical installers and helped to develop standards for the installation and for the conditions of feeding decentralised power into the network (Gabler et al., 1997), i.e. it led to knowledge formation 'downstream'.

However, in the early 1990s, the market was still small, and for the solar cell industry, it was not large enough to justify investments in new production facilities, in particular as the industry was running with large losses (Hoffmann, 2001). Siemens had already bought the US firm ARCO, and Siemens expanded its production there, see table 4.2. The remaining solar cell producers were consolidated into one firm, ASE, in 1994 (Hoffmann, 2001). ASE then bought the US firm Mobil Solar and production of solar cells increased in the US, see table 4.2. At the same time, the German production of solar cells dropped to nearly nil. Hence, by the middle of the 1990s, a crisis emerged where 20 years' worth of investment in RDD could show little both in terms of market development and industrial production.[24]

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the local utility in 1993. The funding of their work on dye-sensitised cells comes largely from the state Nordrhein-Westphalen (Hanke, 2001).

[24] Indeed, the relation between RDD input and output of solar cells was far higher in Germany than in Japan and the US (RDD data from IEA 2001b, production data from PV News).

**Table 4.2 German solar cell production compared to output in the US by the German firms Siemens and ASE, 1983 to 2000**

| Year | Cell production in Germany (MWp) | Cell production in USA by ASE and Siemens (MWp) | German share of total (%) |
|---|---|---|---|
| 1983 | 1.1 | | 100 |
| 1984 | 0.9 | | 100 |
| 1985 | 1.1 | | 100 |
| 1986 | 0.9 | | 100 |
| 1987 | 1.0 | | 100 |
| 1988 | 1.5 | | 100 |
| 1989 | 1.6 | | 100 |
| 1990 | 2.3 | 7.0 | 25 |
| 1991 | 2.9 | 9.0 | 24 |
| 1992 | 3.2 | 9.0 | 26 |
| 1993 | 3.1 | 12.5 | 20 |
| 1994 | 3.1 | 13.6 | 19 |
| 1995 | 1.9 | 19.0 | 9 |
| 1996 | <0.2 | 20.0 | <1 |
| 1997 | 2.0 | 28.0 | 7 |
| 2000 | 17.8 | 33.5 | 35 |

Sources: 1983-1997 PV News, 2000 Photon International

Now began a struggle by the advocates of solar power to strengthen the function ‘formation of markets’ (see section 2). Eurosolar had already proposed a 100 000 roof programme in 1993, and the SPD included that in its political program in 1994, but the CDU/Liberal majority in Parliament rejected the suggestion for a draft law (Scheer, 2001). A larger Federal market formation programme did not, therefore, immediately follow the 1 000 roofs programme. In the absence of a Federal programme to create a market for solar cells, initiatives were taken by a range of other actors.

Förderverein Solarenergie and Eurosolar first put forward the concept of a ‘cost covering feed-in law’ in 1989 (von Fabeg, 2001; Scheer, 2001). This was supported by an industry association organising some 3 500 owners of small-scale hydro power plants (Scheer, 2001) and the infant German wind turbine industry (Ahmels, 1999).

This association, many of its members were politically conservative (Scheer, 2001), campaigned in a larger association organising small and medium sized firms (Mittelstand) for the idea of a law. Within the German parliament, 15-20 politicians from CDU, SPD and the Greens, organised within the Eurosolar Parliamentary Group, also worked for the acceptance of a law. The majority of the CDU members agreed and while the utilities opposed it, the passing of such a law in 1991 was ‘a small thing’ in terms of political efforts (Scheer, 2001).

The law gave the suppliers of electricity from renewable energy technology 90 percent of the domestic market price, nearly 17 pfennig per kWh. For wind power, this was a large sum and the diffusion of wind turbines took off (Johnson and Jacobson, 2000). However, for solar power the sum required to induce rapid diffusion was much higher.

In 1992, the Förderverein Solarenergi proposed that more generous feed-in laws should be applied locally for solar power (von Fabeg et al. 1995). Together with local environmental groups and Eurosolar (Scheer, 2001), work was undertaken to influence local governments. In 1994, a breakthrough came when Aachen became the first city to design and implement such a feed-in law and many other cities (40-45, Scheer, 2001) followed the ‘Aachen model’ (von Fabeg, 2001; Goetzberger, 2000, Scheer, 2001).

In the same year, Bayernwerk introduced the first ‘green pricing’ scheme, which involved investment in a 50 $kW_p$ plant. Shares were sold to about 100 people who paid about 20 pfennig per kWh (Schiebelsberger, 2001). Many such schemes followed, for instance by RWE in 1996. About 15 000 subscribers eventually paid an eco-tariff (twice the normal tariff) for electricity generated by solar cells, hydropower and wind (Mades, 2001).[25]

Due to these initiatives, the market did not disappear at the end of the 1 000 roofs programme but continued to grow, see table 4.2. Whereas the size of the market was quite limited, the large number of cities with local feed-in laws and the proliferation

[25] See also Gabler et al, 1997.

of green pricing schemes revealed a wide interest in increasing the rate of diffusion. Various organisations also lobbied for a program, which would develop a mass market for solar cells. Eurosolar had proposed a programme to cover 100 000 roofs in 1993 and, since 1996, the German Solar Energy Industries Association had worked towards the realisation of such a programme (Bundesverband, 2000).

The lobbying of these organisations, and others that advocated a greater presence of renewable energy technology, was met by opposition from the utilities, with their vested interests in the incumbent technologies. Since 1991, the utilities had had to pay wind power suppliers nearly 17 pfennig per kWh and by the mid 1990s, the utilities worked vigorously to convince Parliament that the Federal feed-in law should be rescinded (Ahmels, 1999, Scheer, 2001). Of course, the lobbying from the utilities was not restricted to wind power but also applied to solar power. In 1997, a select committee with 15 members of parliament was made responsible for investigating whether or not the law should be amended. In the end, the wind lobby won the political battle, though only just. In the select committee, the proponents of a continued law won the vote by eight to seven (Ahmels, 1999, Johnson and Jacobsson, 2002).[26] Hence, in 1997, the wind power lobby had succeeded in keeping a federal legislation, which favoured renewable energy technology, although this was less favourable for solar power.

Lobbying by the German solar cell industry was now intensified. As was shown above, Siemens had already started its production in the US and ASE had the opportunity of doing so with its acquisition of Mobil Solar. To continue the location of production in Germany, without any prospects of a large home market, would clearly be questionable from a firm’s point of view. ASE threatened at this time to move abroad if a market expansion did not take place (Hoffmann, 2001). A promise of a forthcoming programme was then given and ASE decided to invest in a new plant in Germany, manufacturing cells from wafers produced with a technology acquired from Mobil Solar. Production started in mid 1998 (ASE, Press Release, 1998) in a plant with a capacity of 20 MW (Hoffmann, 2001).

The decision to locate it in Germany implied a dramatic increase in the German industry's solar cell production. A second major investment was Shell's entry into the German solar cell industry through their investment in a new plant in Gelsenkirchen in 1998 **(**9.5 MW, Stryi-Hipp 2001**)**. Also here, a dialogue with policy makers preceded the investment (Zijlstra, 2001). Hence, in 1998, two major investments were made which greatly expanded capacity in the German solar cell industry**.**

The market formation programme called for by firms and other organisations was decided upon in 1998 and started in January 1999 under the new Red/Green coalition. The programme aimed at supplying 100 000 roofs with solar cells and involved investment subsidies and low interest rates for owners of solar cells. In 1999 more than 3 500 loans were granted to installations with 9 $MW_p$ (Telthörster, 2000).

A revision of the Federal feed-in law followed.[27] The Greens were inspired by the local feed-in laws and wanted to move this to the Federal level. In doing so, they organised a process involving various environmental groups and the two industry associations (see section 4.1). From these, the Greens received help in terms of both information[28] and support in influencing members of Parliament. In addition, the Greens involved the trade union IG Metall, three solar cell producers and politicians from some Federal states e.g. Nordrhein Westphalia[29] (Pfeiffer, 2001).

The SPD, on the other hand, had an industrial policy interest in re-writing the feed-in law. They feared that the liberalisation of the energy market (1998) would further a longer-term decline in employment in the energy sector and in the associated capital goods industry, which has always been a point of strength for the German industry. At this time, the German wind turbine industry had grown to be the second largest in the world and exhibited great dynamism (Johnson and Jacobsson, 2002). With liberalisation, the price of electricity dropped, and with it, the remuneration for wind turbine owners. It was then feared that the incentive for further diffusion would be

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[26] Scheer (2001) meant that as 20 CDU members of Parliament would have gone against a dismantling of the law, the government could not risk changing the law.
[27] This paragraph is based on Pfeiffer (2001) and Eichert (2001).
[28] Positioning papers were written by, for example, DGS, on the appropriate level of payment per kWh for solar power in the context of such a law (Jannsen, 2000).
[29] Like several other states Nordrhein Westphalia had had its own subsidy program for smaller solar cell plants (Gabler et al. 1997).

lost and that a less dynamic home market would hurt the German wind turbine industry.

In March 2000, the 1991 feed-in law was revised and the remuneration was no longer set as a function of market price, but was fixed for a period of twenty years. Moreover, the remuneration differed between various renewable energy technologies. For solar power, this meant an increase in payment to 99 pfennig,[30] a level which would probably not have been obtained without the very considerable interest in paying for solar electricity as revealed by the numerous local feed-in laws (Scheer, 2001). These two initiatives to form markets resulted in the German market increasing from 12 MW in 1998 to 65 MW in 2001 **(**see table 4.1).

In response to the growing market, both through the earlier local feed-in laws and through the larger scale programmes at the end of the period, a range of entrants began to enlarge the technological system, forming a more elaborate division of labour.[31] In this process they strengthened the system not only by 'supplying resources' and 'creating knowledge', much of it 'downstream' and in production technology, but also by developing *new market segments*.

The bulk of the new market was the *roof top* market and a large number of electrical firms installing home solar cell systems emerged (Goetzberger, 2000). These were able to benefit from courses in solar cell technology by both module manufacturers, such as Solarfabrik (Boerner, 2000), and by the formal education system where courses in solar cell installation are available at the secondary level (Boerner, 2000)

More technically demanding applications were found in *facade and roof integrated* solar cell systems. In 1991, the first building integrated (facade) solar cell plant was completed (Beneman et al., 2001). The buyer was the local utility in Aachen and the

[30] This refers to the installations made in year 1. For installations made in subsequent years, the remuneration is reduced by a predetermined amount. In this connection, the lending conditions within the 100 000 roof programme were made somewhat less attractive but the number of applicants still rose (Telthörster, 2000).

[31] Some firms were induced by other factors, For instance, Wurth Solar, see Box 2, was founded by a distributor of solar cells as a means to reduce dependence on the established solar cell firms. The market for the distributor was not primarily the German but the global, including developing countries (Dimmler, 2000).

supplier was Pilkington (later Flabeg), which diversified into solar cell facades from glass manufacturing. An essential part of the work by this first mover was to educate electricians, builders, facade makers and, in particular, architects in solar cell technology (Chehab, 2001), see Box 1.

Other firms entered into this application. One, which was a spin-off from a Fraunhofer institute, failed when its industrial partner went bankrupt but others survived, e.g. Solon, which entered in 1997, (Stryi-Hipp, 2001) and new entrants are still coming in, e.g. Okalux together with the module manufacturer Solarfabrik (Boerner, 2000; Photon, May 2001).

The first entrant into roof-integrated solar cells was Lafarge in 1995. Being the dominant actor in the tile industry in Germany, management sought not only to strengthen its image of leadership by diversification but also to influence the direction of development (Neuner, 2001). As with Pilkington, Lafarge needed to invest in educating and convincing not only its own sales staff of 200 people of the benefits of roof integrated solar cells, but also architects, building contractors and electricians. Indeed, in 2000, they took the initiative of bringing together different industry associations, whose members are involved in the diffusion process, in order to promote the use of solar cells (Neuner, 2001). The interest in this application grew and in 2000, there were ten firms showing roof integrated solar cells at an exhibition (Neuner, 2001). Indeed, Germany is seen as the world leader in roof integrated solar cells (Maycock, 2000).

A range of firms entered 'upstream' too in the 1990s.[32] The number of *solar cell* manufacturers rose from two in 1996 to six in 2000, establishing a German presence

[32] Many of the investments undertaken by new entrants, or by existing firms, have been partially financed by various types of Federal and State subsidies. The 'supply of resources' went beyond funding provided by the Federal RDD programme – an industrial policy can be discerned. For example, in the cases of the new ASE plant, the Shell plant and the plant developed by Wurth Solar, Federal and State support amounted to about 40 per cent of the costs, excluding building costs (ASE, Press Release, 1998; Dimmler, 2000; Zijlstra, 2001). Antec Solar raised 60 million DM through other government channels (see Box 2) but much private capital was also mobilised. Some firms (e.g. Solarfabrik and Solar Strom AG - which build plants on rooftops and sell the electricity) raised capital from a large number of individuals (Boerner, 2000). Indeed, private capital appears to be very willing to invest in solar cell firms, even in more untried design approaches such as the Graetzel cell (Hanke, 2001).

in a wide range of design approaches (aSi, CIS, CdTe, etc). [33] In addition to ASE and Siemens, Ersol began crystalline cell production in 1997 (Stryi-Hipp, 2001; Schmela, 2001a). Sunways, established in 1999 (Stryi-Hipp, 2001), produces semi-transparent cells exploiting knowledge developed at the University of Konstanz. Antec Solar builds on research in the Batelle institute on CdTe cells and is now constructing a 10 MW plant; see Box 2 (Bonnet, 2000). Wurth Solar uses knowledge developed over 20 years by the University of Stuttgart and the R&D institute ZSW in building a 10 MW CIS plant, see Box 2 (Springer, 2000, Dimmler, 2000). A seventh firm has started building a polycrystilline factory (Qcells, see Schmela, 2001b) and an eighth has announced an entry, MVV, a utility using acquired US CIS technology (Cameroon, 2001).[34] As importantly, ASE recently (April 2001) announced that it will increase its capacity from 20 to 80 MW,[35] another leap in the German production capacity (Schmela, 2001,c).[36]

[33] Production of Graetzel cells may well start too within a year (Hanke, 2001).
[34] According to Renewable Energy Report 32, October 2001, MVV will also produce aSi cells.
[35] Local production lags the development of the market. In 2000, German solar cell production amounted to only 17.8 MW (Schmela 2001,b) and imports dominated consumption. However, we expect this pattern to change, as the investments in factories described above, will increase the German production capacity of solar cells greatly.
[36] Module manufacturing has received new entrants too (Stryi-Hipp, 2001). As mentioned above, Solarnova entered in 1995 (Stryi-Hipp, 2001) and Solarfabrik started production in 1997 (Boerner, 2000). BP Solar, the world's leading firm, recently announced it would build a 20 MW module plant in Germany. Germany was chosen since it is "a leading market" (Kreuzmann and Schmela, 2001b).

**Box 1 Developing a new application – the case of Flabeg**

Flachglass, the German part of Pilkington, started working on solar cell facades in 1989. The first project started when an architect, who was contracted to design an official building in Aachen, took part in a small meeting on solar cells. Another participant was Mr. Chehab of Flachglass. Mr. Chehab had earlier worked in a small firm which was involved with solar cell tiles etc. In the evening the architect and Mr. Chehab started talking and the architect was convinced that he had seen solar cells incorporated into the Centre Culturelle Arabic in Paris. Mr. Chehab was able to convince him though that this was not the case but said that if he wanted a solar cell facade, he could get it. It was the local utility in Aachen that had asked for such a façade, a 4kWp installation. Mr. Chehab convinced his management of the idea and made a prototype in the laboratory, which was to the liking of the architect. Federal funding was requested but denied since it was believed that solar cells should be put on top of the roofs in order to maximise output. The project continued anyway and later in the year, the building was in place. The next project was in 1991, again 4 kWp, and again financed fully by a local utility (in Hanover). The interest of the local utilities was explained by a desire to explore the impact of, and difficulties associated with, feeding solar cells generated electricity into the net (as this was the time of the 1 000 roof s programme), but it was also a way of trying something new.

After the first project Flachglass tried to spread information about this new application for solar cells. The Aachen project was well documented in newsletters and in architectural magazines and architects came to look at it, even from Japan and US. Politicians and architects were continually invited and training programmes were given for electricians, facade makers and building companies. Flaschglass even wrote a handbook of solar architecture. They developed good relationships and important contacts for their facade projects, with building institutes, mainly locally. After designing their solar facade houses, some of the architects involved were given professorships in solar architecture. Their relationship with architects led them to understand that technology was needed to ensure that different types and sizes of modules could be combined (to enhance the aesthetic feature of the installation). They then developed this technology together with a partner. So far (2001), they have been involved in about 350 solar cell projects all over the world. The largest is the 1 MW building for the Fortbildungsakademie in Herne. Mr Chehab is convinced that the very visible installations have influenced politicians' and the public's perception of solar cells and helped to lay the ground for the 100 000 roof and the 99 pfennig programmes.

**Box 2 New start-ups in thin firm solar cells – the cases of Wurth Solar and Antec**[37]

The knowledge exploited by *Wurth Solar* dates back to the 1970s and the build up of academic research on CIS at the IPE of the University of Stuttgart, research which is continuing today. In 1987, a group of professors at that University started a research institute, ZSW, together with the Federal and Baden Wurtenberg governments and some firms. ZSW is today the largest research unit in Germany in CIS technology, indeed, larger than that of Siemens. After some years, ZSW began to shift towards more applied work. With both Federal and other funding, and working closely with IPE, they began to scale up the 10 by 10 cm modules made earlier by IPE to 30 by 30 cm in 1994. In 1996, they worked closely with ASE to develop an industrial production of CIS but ASE decided to withdraw from the project due to high perceived risk and costs of upscaling (Maurus and Schade, 2001; Hoffmann, 2001). In 1998, ZSW had stabilised yield to 13% and decided to go for pilot production. Discussions were then held with several venture capitalists but ZSW felt they needed to have an industrial partner, one which had a longer time horizon and which could supplement the knowledge base of ZSW. Then Wurth came into the picture. Wurth has a turn-over of 8 billion DM and is present in 75 countries as a distributor of, for instance, electronics products and building products and had started to distribute solar cells in 1996. Wurth has a record of thinking long term and had competence in related areas (e.g. production of printed circuit boards and building facades). Wurth Solar was established as a means for Wurth to go deeper into the fabrication of solar cells and to reduce the dependence on other manufacturers. Wurth Solar has, so far (Nov 2000), invested about 20 million DM of which 8 million has come from State and Federal sources. It is estimated that it will cost up to 50 million DM to build a 10 MW plant. In the start-up of Wurth Solar, 4-5 staff from ZSW moved to the new firm. Moreover, ZSW's solar division acts as the research arm of Wurth Solar, which has the exclusive rights for the commercialisation of ZSW's technology. Wurth Solar will not develop its own R&D unit. In filling this role, ZSW continues to receive a great deal of Federal RDD funding and maintains its close relationship with IPE. The focus today is to upscale the cells from 30 by 30 to 60 by 60 cm (their goal is to make 120 by 120 cm). Academic-industry links probably do not come closer than this.

Research at the Batelle Institute preceded the formation of *ANTEC Solar* in 1996 by about 25 years. In response to demand from the European Space Agency, Battelle started to work on cadmium telluride/sulfide cells in about 1971. At the time of the renewed interest in solar cells at the end of the 1970s, they left the cadmium telluride cell (due to generally perceived mistrust of this alternative) and began working on cadmium selenide financed by the Federal government and by the European Union. This work continued for a decade until it was stopped due to fundamental problems with the technology. In 1990, a student wanted to do her diploma work on solar cells and received the suggestion to do it on cadmium telluride. After 6 months she came back with a cell with 7 per cent efficiency, which was high, and Batelle put some of its own money into developing it further. They received some funding in the period 1990 –1993 from the EU but not from the Federal government due to a perceived danger of using cadmium. They did not get any Federal RDD money until 1997. In 1993, the Batelle Institute closed down and four of its members started the firm Antec to commercialise some of the technology, including solar cells, developed by Batelle. Antec Solar was founded in 1996 after they had managed to raise about 60 million DM for the purpose of building a 10 MW plant. The money was raised using a number of sources. First, as starters of a new firm they benefited from a credit scheme where the state guaranteed the payment of the loans and where no security was required. Second, a technology transfer programme to the new States gave subsidies equivalent to 50 per cent of the investment costs. Third, the large engineering firm Balcke-Durr, invested some money and, fourth, credit for 20 million was given by the State banks of Hessen and Thuringen where they located their factory. Antec Solar is attempting to develop a 10 MW factory directly but in parallel they have produced 30 by 60 cm cells in a lab in Kelkheim, which is currently being transferred to the factory in Rudisleben. This upscaling is partly funded by the Federal RDD program and they have also received some smaller funding from the EU. Very substantial problems need to be tackled in the production process. Balcke-Durr, with experience in contracting work, is heading that work, which involves finding a range of contractors who are prepared to design custom-made units and not sell these to other firms. So far (2000), they have not mastered the whole production process and they do not expect to be fully operational until 2002.

[37] This box is based on Dimmler (2000), Schaeffler (2000) and Springer (2000).

The new entrants, both 'upstream' and 'downstream', as well as other organisations, were linked in three types of increasingly powerful networks. First, the strong knowledge base in the German universities and research institutes made them attractive partners for R&D units in the solar cell industry (Hoffman, 2001, Stierle and Einzinger, 2001, Maurus and Schade, 2001), 'Creation of knowledge' 'upstream', and the sharing of that knowledge, is carried out to a great degree in such relationships.[38] Close industry-academia links were developed as manifested by, for instance, firm representatives on the Advisory Boards of academic units and the transfer of knowledge from academia to industry (Stierle and Einzinger, 2001, Hoffman, 2001, Maurus and Schade, 2001). The RDD policy was conducive to the establishment of industry-academia links, in that funding agencies require that collaboration takes place (Stierle and Einzinger, 2001) and that industry has to confirm that the research project is important for industry (Maurus and Schade, 2001).[39]

Second, industry-academia links evolved 'downstream'. As new applications are developed, relations need to be established, and 'knowledge created' together with actors, who have an influence on the investment decisions in these applications. In particular, relations to architects have been identified as critical (Jannsen, 2000; Chehab, 2001). Indeed, it was specifically pointed out that as a result and indication of a learning process, some architects have received professorships in solar architecture (see Box 2), which enlarges, and 'supplies resources', to the technological system.

Third, with the large number of new entrants, the strength by which the industry associations can operate as pressure groups increased. They face the challenge of maintaining a regulatory framework for solar cells, which upholds the powerful

[38] Indeed, in the case of the start-up Wurth Solar, the links with the Research Institute ZSW and, indirectly to the University of Stuttgart, are very tight, see Box 2.

[39] In addition, the Bavarian government financed a program with the purpose of strengthening industry-academia links in solar cells and a senior researcher in Siemens was suprised how quickly Universities which previously had not worked on solar cells could become useful (Stierle and Einzinger, 2001)

momentum of the last 5-6 years. [40] The key function for doing so is 'Market formation' where a decision on the future of the feed-in law will need to be taken by the German parliament before 2003.[41] The importance of a continued 'market formation' policy is appreciated when we understand the strength of current investments into the solar cell industry.[42] This is a clear sign of an industry, which is committed to a strong expansionary phase, but also one which is very vulnerable to a decline in the market.

In sum, an intense struggle to alter the institutional framework led to a rapid increase in the market in this second period. Whereas the generation of knowledge associated with Federal RDD funding continued to be substantial and diverse in nature, knowledge was now being created in the whole value chain, reflecting a range of new entrants and development of a division of labour in the technological system. In that process, the five functions were strengthened. This applied not only to the two hitherto very weak functions (market formation, creation of external economies) but also to the other three; 'creation of knowledge' took place throughout the whole value

[40] In this they were greatly aided by the recent (2001) European Court decision that the German feed-in law was not against European Law, as argued by the utility Preussen Elektra (Kreutzmann and Schmela, 2001a, page 12). Preussen Elektra argued that the Feed-in law represented an amended system of state aid but the Court ruled that since the Law does not involve any transfer of state resources it is not state aid in the meaning of the Treaty (Kreuzmann and Schmela, 2001a, p. 12).

[41] The industry associations face the additional challenge of rectifying underdeveloped 'knowledge creation' and diffusion in the machinery industry serving the cell manufacturers. In part, this is due to an earlier lack of emphasis on production technology development within the context of the Federal RDD programme (Zijlstra, 2001; Hoffman, 2001, Stierle and Einzinger, 2001), but it may also be related to a weakness in the European industry in electronics production (Stierle and Einzinger, 2001). In thin-film manufacturing, firms are struggling, and investing a great deal of money, to develop automated plants, involving a substantial 'creation of knowledge'. This has been fraught with difficulties. There are no suppliers of such plants and the firms have either had to develop parts themselves or convince suppliers of related equipment to apply their skills to solar cell manufacturing. In crystalline cell manufacturing, functioning production technology has been around for many years but there are 'enormous possibilities for innovations and for tremendous steps forward' by drawing on the skills of the machinery industry supplying the electronics industry, e.g. CD player industry (Zijlstra, 2001). However, as new knowledge about the production process is created, the firms seek to keep that knowledge in-house or prevent suppliers from selling the machinery to other firms by contractual arrangement. In other words, the firms are trying to 'go it alone' to a certain extent and not to share their knowledge. This is serious as it hinders the evolution of a specialised supplier industry and the 'creation of external economies' mediated through such an industry. Clearly, an industry-wide effort to encourage an appropriate division of labour may be required.

[42] It is also vital to the solar cell industry of other European nations who face small home markets. French Photowatt and Spanish Isophoton are well known examples of European firms who benefit from the German market growth but less well-known is the Hungarian aSi producer Dunasolar which is to supply 125 000 aSi modules 5 MW plant in Germany (New Energy, August 2001, p. 70). Unless other European nations follow Germany in designing market formation programmes, the future of the European solar cell industry rests on the decision taken by the next German government (election 2002).

chain; the ‘supply of resources’ came from a greater number of sources and the ‘direction of the search process’ began to be strongly guided by the growth potential of solar cells.

In contrast to the first period, we can see the beginnings of a process of cumulative causation. Two examples will be given. First, market formation guided the direction of search (growth), which led to new entrants (and to expansionary investments). The new entrants were central to the development of applied knowledge (in the firms and around them) and of new market segments (e.g. roof and facade-integrated solar cells). Second, new entrants, as well as the revitalised incumbents, strengthened the power of the pressure groups to influence the design of a favourable market formation programme. The challenge to the technological system is to strengthen these virtuous circles so that the growth of the system will be increasingly self-sustained. This involves, in particular, maintaining a favourable regulatory framework.

## 5. Discussion and key policy challenges

We set out with the aim of improving our understanding of the transformation process, and associated key policy challenges, in the energy sector by examining the emergence of the German technological system for solar cells. We have traced how changes in the constituent elements of the technological system have influenced a series of functions; we have mapped the functional pattern of the system and what factors and which actors have driven this evolution.

From our understanding of the evolution of the German technological system for solar cells, we can identify three main themes and an associated set of policy challenges. The first theme is the key role of organisations that articulate underlying values in favour of solar cells, and other renewable energy technology, and legitimate the new technology. Much of the work of these organisations is to influence the regulatory framework so that markets can be formed and values be expressed in terms of changing consumer demand. This work is essentially political in nature and involves building coalitions of actors in favour of the new technology. Indeed, the work of many German pressure groups, working with representatives of the new industry and politicians, to strengthen the function ‘formation of markets’, proved to be critical for the evolution of the technological system – together they formed a coalition of system builders. The policy challenge here lies in foiling attempts by vested interests to capture the state and block a transformation by having many more resources at their disposal than the representatives of infant industries and underdeveloped markets.

The second theme is the length of the ‘learning period.’ For solar cells, this will last several decades if it is defined as starting with the RDD programme in the mid 1970s and ending when the cost of solar cells is somewhat closer to that of other power technologies. Indeed, signs of a self-reinforcing process could not be seen until about the mid 1990s, i.e. after about two decades of activities in Germany. The process of maturation includes not only a political battle over the regulatory framework (which takes time) but also the entry of many firms into the whole value chain, i.e. silicon suppliers, wafer producers, cell producers, system engineering firms, application specialists, firms supplying building integrated solutions, architects and electricians, etc. These firms need to acquire resources, to experiment with the new technology and to learn as well as teach about the new technology (see Boxes 1 and 2 as well as the case of Lafarge referred to above). In this process, new networks need to be formed to enhance the learning (and to strengthen the new technology in the political battle). In addition to these firms, financial institutions, educational institutions, insurance companies, city planners etc. need to learn about solar cells and to develop a policy towards it. Without prior extensive learning, diffusion on a large scale will simply not be able to take place.

The policy challenge here is two-fold. First, the new technologies need to be given a ‘space’ in which a learning process can take place. This space cannot be created by technology policy alone but requires measures designed to form markets in order to induce firms to enter into various points in the value chain. Without markets, firms will hesitate to enter and a process of cumulative causation (including a strengthening of coalitions favouring solar cells) will not be set in motion. Second, policy makers need to expand this space in order to strengthen the process of cumulative causation (e.g. induce even more firms to enter), and have the patience to maintain this growing space over an extensive period of time in a context where vested interests challenge the relevance of such support.

The third theme is the great uncertainties over the potential performance and cost of the various competing designs. There are numerous examples where firms and other research organisations have spent many years researching a particular design approach, only to abandon such efforts in the face of technical problems or in terms of continued high uncertainty about the outcome of further efforts. For instance, Batelle Institute spent a decade working on Cadmium selenide only to abandon it due to stability problems. At the policy level, an earlier hope of being able to identify a key challenger to crystalline silicon has given way to funding of several competing thin-film designs. More are coming and diversity is driven by an awareness that solar cells need to increase their price/performance greatly in order to be able to compete in larger segments. Policies directed towards creating a 'space' for solar cells, i.e. market formation policies, therefore need to coexist with policies aimed at maintaining variety.

The need to generate and sustain a variety of design approaches is acknowledged by policy makers but there is a downside to variety in terms of costs. Variety reduces the scope for volume production and obtaining simple scale and learning economies.[43] The policy challenge is therefore not only to be able to run parallel policies directed towards markets and towards science but also to balance the conflict between volume and variety.

[43] A variety of approaches may also act as an additional impediment to the development of a capital goods sector since the machines used are not universal. For instance, CIS can be produced in two different processes, which creates additional uncertainty for the capital goods sector (Goetzberger, 2000).

## References


Ahmels, H. (1999): Interview with Dr. Hans Peter Ahmels, BWE, October 8th.

Annan, R. H. and Rannels, J.E. (1991): U.S.A. Photovoltaics Program Plan FY 1991 – FY 1995, 10th European Photovoltaic Solar Energy Conference, Lisbon, Portugal, pp 1371-1374.

ASE (1998): Press release, August 31. ASE Initiates First Industrial-scale Manufacturing of Innovative Ribbon Silicon Solar Cells in Alzenau, Germany.

Benemann, Joachim, Oussama Chehab and Eric Schaar-Gabriel (2001): Building-integrated PV modules, *Solar Energy Materials & Solar Cells*, pp 345-354.

Bergek, A. (2002): *Shaping and Exploiting Technological Opportunities: The Case of Renewable Energy Technology in Sweden*, PhD thesis, Department of Industrial Dynamics, Chalmers University of Technology, Gothenburg, Sweden.

Boerner, B. (2000): Interview with Ms Barbara Boerner, Solarfabrik, November 13th.

Boiko, B. (1974): UNESCO activities in the field of solar energy applications, Proceedings of the International Conference on Photovoltaic Power Generation, Hamburg, Deutche Gesellschaft fur Luft und Raumfahrt e. V., Köln, pp 9-18.

Bonnet, D. (2000): Interview with Dr. Dieter Bonnet, Antec Solar, November 16th.

Bundesverband, (2000): Solar Who's Who? The Compendium of the German Solar Industry, Munich.

Cameroon, R. (2001): Interview with Dr. Murray Cameroon, EPIA, May 7th.

Carlsson, B., ed. (1995): *Technological Systems and Economic Performance: The Case of Factory Automation*, Kluwer Press, Boston/Dordrecht/London.

Carlsson, B., ed. (1997): *Technological Systems and Industrial Dynamics*, Kluwer Press, Boston/Dordrecht/London.

Carlsson, B., ed. (2002): *Technological Systems in the Bioindustries. An international study,* Kluwer Press, Boston/Dordrecht/London.

Carlsson, B. and Stankiewicz, R. (1991): On the Nature, Function, and Composition of Technological Systems, *Journal of Evolutionary Economics*, 1 (2), pp 93-118.

Carlsson, B. and Jacobsson, S. (1997): Diversity creation and technological systems: a technology policy perspective, in C. Edquist (ed.), *Systems of Innovation: Technologies, Institutions and Organizations*, London: Pinter Publishers, pp 266-297.

Carlsson, B., Holmen, M., Jacobsson, S., Rickne, A. and Stankiewicz, R. (2002): The analytical approach and methodology, in Carlsson, B., ed. *Technological Systems in the Bioindustries. An International Study,* Kluwer Press, pp 9-34.

Chehab, O. (2001): Interview with Mr. Oussama Chehab, Flabeg Solar International, March 9.

DFS (2000): Deutscher Fachverband Solarenergie: DFS-Statistik Photovoltaik 1990-2003, stand: 23.06.2000, Freiburg.

Dimmler, B. (2000): Interview with Dr. Bernard Dimmler, Wurth Solar, November 14th.

Edquist, C. and Johnson, B. (1997): Institutions and Organizations in Systems of Innovation, in Edquist, C., ed: *Systems of Innovation: Technologies, Institutions and Organizations,* Pinter, London, pp 41-63.

Eichert, M. (2001): Interview with Marcus Eichert, Scientific Advisor to Volker Jung, member of the German Parliament (SPD), October 4th.

EPIA (1995): European Photovoltaic Industry Association. Photovoltaics in 2010. Vol. 1-4. European Commission, Directorate General for Energy, Brussels.

Fraunhofer, (n.d.): Solar Electricity from a Thousand Roofs, Fraunhofer Institute for Solar Energy Systems, Freiburg.

Von Fabeg, W. (2001): Interview with Wolf von Fabeg, Forderein Solarenergie, March 7.

Von Fabeg, W., Kreuzmann, A. and Welter, P. (1995): A new path to self-sustaining markets for PV – the Aachen model. 13th European Photovoltaic Solar Energy Conference, 23-27 October, Nice, France.

Gabler, H., Heidler, K. and Hoffmann. U. (1997): Market introduction of grid-connected photovoltaic installations in Germany. 14th European Photovoltaic Solar Energy Conference, Barcelona, Spain, 30 June- 4 July.

Goetzberger, A. (2000): Interview with Professor Adolf Goetzberger, Fraunhofer Institute, November 11.

Goldberg, M. (2000). Federal energy subsidies: not all technologies are created equal. Renewable energy policy project, Washington, DC.

Green, M. A., Emery, K., Bücher, K., David, K. I. and Sanekazu, I. (1999): Solar cell efficiency tables (version 14). *Progress in Photovoltaics* 7, pp 321-326.

Greenpeace and EPIA (2001): *Solar Generation. Solar Electricity for over 1 Billion People and 2 Million Jobs by 2020*, Greenpeace and the European Photovoltaic Industry Association.

Hanke, P. (2001): Interview with Dr. Klaus Peter Hanke, INAP, March 7.

Herwig, L. O. (1974): Report on photovoltaics research and technology in the United States, Proceedings of the International Conference on Photovoltaic Power Generation, Hamburg, Deutche Gesellschaft fur Luft und Raumfahrt e. V., Köln, pp 29-42.

Hoffmann, W. (2001): Interview with Winfred Hoffmann, AES, March 5.

Hughes, T. P. (1983): *Networks of Power*. The Johns Hopkins University Press. Baltimore.

IEA (1997): International Energy Agency. Annual Report 1997, Implementing Agreement on Photovoltaic Power Systems.

IEA (1999): International Energy Agency. Annual Report 1999, Implementing Agreement on Photovoltaic Power Systems.

IEA (2000): International Energy Agency. Trends in Photovoltaic applications in selected IEA countries between 1992 and 1999. Report IEA-PVPS T1-08: 2000.

IEA (2001a): International Energy Agency. Trends in Photovoltaic applications in selected IEA countries between 1992 and 2000.

IEA (2001b): International Energy Agency. Energy Technology RDD Statistics. http://www.iea.org/stats/files/rd.htm, Accessed 2001-06-15.

Jacobsson, S. (2002): Om konsten att omvandla energisystemet – reflektioner kring 'Handel med certifikat. Ett nytt sätt att främja el från förnybara energikällor, SOU 2001:77', *Ekonomisk Debatt*, Årgång 30, 3, pp 265-270.

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

Jannsen, S. (2000): Interview with Professor Sigrid Jannsen, DSG, November 10.

Johnson, A. and Jacobsson, S. (2002): The emergence of a growth industry – the case of the wind turbine industry in Sweden, Germany and the Netherlands, in Metcalfe, S. & Cantner, U. (forthcoming): *Transformation and Development: Schumpeterian Perspectives* (provisional title). Physica/Springer, Heidelberg.

Kazmerski, L. L. (1997): Photovoltaics: A review of cell and module technologies, *Renewable and sustainable energy reviews* 1, pp 71-170.

Kreuzmann, A. and Schmela, M. (2001a): Neither state aid nor trade barrier, *Photon International*, April, p.12.

Kreuzmann, A. and Schmela, M. (2001b): BP Solar to build 20 MW plant in Germany, *Photon International*, May p. 11.

Macomber, H. L. (1980): Application trends for photovoltaics, 3rd E.C. Photovoltaic Solar Energy Conference, Cannes, France, pp 30-39.

Mades, U. (2001), Interview with Uwe Mades, RWE Power, March 7.

Maurus H. and Schade, H. (2001): Interview with Hermann Maurus and Horst Schade, RWE Solar (formerly ASE), Division Phototronics, May 8th.

Maycock, P. D. (1985): The current PV scene worldwide, Proceedings of the 6th E.C. Photovoltaic Solar Energy Conference, London, UK, D. Reidel Publishing Company, Dordrecht, pp 21-27.

Maycock, P. D. (1986): *PV News* 5(2), pp 1-8.

Maycock, P. D. (1996): Photovoltaic technology, performance, cost and market, Photovoltaic Energy Systems, Catlett, VA, USA.

Maycock, P. D. (2000): *Renewable Energy World*, 3(4), pp 59-74.

Myrdal, G., (1957): *Economic Theory and Under-developed Regions*, London: Ducksworth Pubs.

Neuner, R. (2001): Interview with Mr. Roland Neuner, Lafarge Brass Roofing Accessories, March 5.

*New Energy*, August (2001): Big solar power stations for Mecklenburg-West Pomerania and Thuringia, p. 70.

Norberg-Bohm, V. (2000): Creating incentives for environmentally enhancing technological change: lessons from 30 years of U.S. Energy Technology Policy. *Technological Forecasting and Social Change* 65, pp 125-148.

Palz, W. and Kaut, W. (1985): Photovoltaics in the European Community, 6th E.C. Photovoltaic Solar Energy Conference, London, UK, pp 11-20.

Pfeiffer, C. (2001): Interview with Carsten Pfeiffer, Scientific Advisor to Hans-Josef Fell of the German Parliament (the Greens), October 4th.

Photon, (2001): Okalux offers modules for façade integration, May, p. 33.

Porter, M. (1998): Clusters and Competition. New agendas for companies, governments and institutions, in M. Porter (ed): *On Competition*, Boston: A Harvard Business Review Book, pp 197-287.

Prince, M. B. and Barrett, A. L. (1982): United States federal photovoltaic program status, 3rd E.C. Photovoltaic Solar Energy Conference, Cannes, France, pp. 20-27.

Renewable Energy Report 32, October 2001, p. 28.

Rickne, A. (2000*): New Technology-Based Firms and Industrial Dynamics. Evidence from the Technological System of Biomaterials in Sweden, Ohio and Massachusetts*, PhD Dissertation, Industrial Dynamics, Chalmers University of Technology, Gothenburg, Sweden.

Schmela, M. (2001a): Umweltskontor buys Ersol, *Photon International*, February, p. 11.

Schmela, M. (2001b): PV in the fast lane. Market survey on world cell production in 2000. *Photon International*, March, pp 32-35.

Schmela, M. (2001c): At Staffelstein, the glass is half empty, *Photon International*, April, p.14.

Schmela, M. (2002): Staffelstein misses the point, *Photon International*, April, p. 16.

Schaeffler, R. (2000): Interview with Raymond Schaeffler, Wurth Solar, November 14th.

Schiebelsberger, B. (2001): Interview with Bruno Schiebelsberger, EON, May 9th.

Scheer, H. (2001): Interview with Herman Scheer, Member of the German Parliament and President of Eurosolar, October 5th.

Schock H.-W. and Pfisterer, F. (2001): Thin-film solar cells: Past, present and future, *Renewable Energy World* 4(2), pp 75-87.

Shah, A, Torres, P., Tscharner, R., Wyrsch, N. and Keppner, H. (1999): Photovoltaic technology: the case for thin-film solar cells, *Science*, 285, pp 692-698.

Smith, A. (1776): The Wealth of Nations, London.

Springer, J. (2000), Interview with Johann Springer, ZSW, November 14**.**

Stierle, R. and Einzinger R. (2001): Interview with Roland Stierle and Richard Einzinger, Siemens Solar, May 9th.

Stryi-Hipp, G. (2001): Shine on Deutschland, in *New Energy*, April 2001, pp 40-41.

Telthörster, S. (2000): Interview with Silke Telthörster, Kreditanstalt für Wiederaufbau (Kfw), November 16.

Unruh, G.C. (2000): Understanding carbon lock-in, *Energy Policy* 28, pp 817-830.

Walker, W. (2000): Entrapment in large technology systems: institutional commitment and power relations, *Research Policy* 29, pp 833-846.

Watson, J. (1997): The technology that drove the 'dash for gas', *Power Engineering Journal*, February, pp 11-19.

Wolf, M. (1974): Historic development of photovoltaic power generation, International Conference on Photovoltaic Power Generation, Hamburg, pp 49-65.

www.iea.org 0609001

Young, A. (1928): Increasing Returns and Economic Progress, *Economic Journal* 38, pp 527-542.

Zijlstra, S. (2001): Interview with Mr. Sjouke Zijlstra, Shell Solar Deutschland, March 8.

Zweibel, K. (1995): Thin films: past, present, future, *Progress in Photovoltaics* 3(5), pp 279-293.

Zweibel, K., Ullal, H. S. and van Roedern, B. (1996): Progress and issues in polycrystalline thin-film PV technologies, in Gwinner, D. (ed.) NREL Pre-prints for the Photovoltaic Specialists Conference of IEEE 25, NREL, Golden, pp 159-164.