Functions of Innovation Systems Analysis over time of PV technologies in Germany

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Executive Summary

The call for renewable energy sources has been growing over the past decades. One of the technologies with the most potential is photovoltaic (PV) technology. In PV-cells sunlight is converted into electricity, and sunlight is a practically endless source of energy. PV technology is a common term for a number of distinct PV technologies that share basic principles, but do have important technological differences. Besides technological differences, there are a number of differences which relate to the context around the technology. For example, the amount of government funding for R&D differs amongst the PV technologies, as well as their respective market shares. The PV technologies under study in this thesis are (broadly): crystalline silicon solar (c-Si), thin film (TF) and organic photovoltaic technology.

In order for PV technology to contribute significantly to a sustainable energy household, it is necessary that it is widely used in order to replace a significant share of traditional non sustainable energy sources. In other words, the technology must diffuse. This diffusion of PV technology over time differs strongly per country. In this thesis the diffusion of PV technology in Germany is studied, due to the fact that Germany is one of the leading countries in terms of installed capacity of PV systems. By contrast, in the Netherlands the diffusion of PV technology was much less successful. This points to differences in the ability of both countries to diffuse PV technologies; the PV technologies are the same, but the installed capacity of PV systems (per capita) are very different. It is then relevant for countries such as the Netherlands to gain insight into how this rate of diffusion of PV technology came about in Germany, so that lessons can be learned in order to facilitate better diffusion in the Netherlands. Also important in this regard is to distinguish between the different PV technologies. These PV technologies are different in a number of ways as has been mentioned, and generic insights are difficult to translate to effective policy that applies to different PV technologies. Therefore, in this thesis the insight is gained with a focus on the development and diffusion of different PV technologies in Germany with respective to each other over time. The main research question to be answered is:

What has been the state of functioning of and competition between the three generations of PV in Germany between 1950-2012?

This will be investigated using the Functions of Innovation Systems approach. The kind of system that will be studied is the Technology Specific Innovation System, which is defined by Hekkert and Negrto (2008) as:

A network or networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilize technology.

In order to evaluate the ability of the innovation system to develop and diffuse the technology, necessary functions that must be functioning have been identified by scholars. In this thesis seven functions will be evaluated for the different PV technologies:

1. Entrepreneurial activity
2. Knowledge development
3. Knowledge diffusion
4. Guidance of search
5. Market formation
6. Resources mobilization
7. Advocacy coalitions.

Furthermore, the development and diffusion of the PV technologies respective of each other is studied.

It was found that the functions in the innovation systems of the different PV technologies under study were not functioning alike over time. For crystalline silicon (c-Si) PV technology in the early times of PV technology in Germany it was found that the functions were functioning, but that the expectations and the Guidance of search function was working more in the favor of thin film PV technologies, leading to increased R&D into thin film PV technologies. At the same time however, Market formation and knowledge regarding the application of thin film PV lagged behind compared to c-Si PV due to a lack of demonstrations of the thin film technology. This trend continued up to the late nineties. R&D was done and had been done in thin film PV technologies, but demonstration projects implicitly favored c-Si technology as the technology to be used in such projects, mainly due to the gained experience with this technology and economic reasons. Yet, the amount of R&D from institutions into thin film technologies surpassed the R&D into c-Si technologies, suggesting that the functions were not really aligned as this knowledge did not get much chance to turn into business. At the same time the advantage of this was that there was a PV technology (c-Si) up and working, creating further expectations for PV in general. In the meantime technologically (still) inferior thin film PV technologies had the chance to further develop. At this time the PV market was not large in Germany yet, and there were no sufficient incentives yet to facilitate large scale diffusion of PV into society.

This changed with the advent of the 100,000 roofs program, a low interest loan program for investors that wanted to buy a PV system, and the famous feed-in law, allowing owners of PV systems to feed their generated electricity back into the grid for money. However, these market formation incentives mainly favored the c-Si PV technology, as c-Si PV was still the most used and economic option at this time. Thus c-Si PV modules experienced a wide spread diffusion, while for thin film PV technologies this was much less the case. This lead to a flourishing of other functions in the innovation system of c-Si PV such as Entrepreneurial activities (the market grew, so there was more money to make) and Knowledge development (as c-Si was now becoming more practically relevant than thin film PV technologies) relative to thin film technologies. However, as the diffusion of c-Si PV technology continued, the supply of silicon became tight and the need for alternative PV technologies grew, which is partly why the R&D into organic PV technology experienced a rapid increase around 2005, even though widespread diffusion in the market is still not in sight. Thus it can be said the innovation system for c-Si PV was functioning more comprehensively in comparison to thin film and organic PV technologies, as these thin film and organic PV technologies could not benefit from the market formation programs to the same extent as c-Si PV. However in recent times the different PV technologies (excluding organic PV) are coming closer together in terms of cost/kWh, and the with only the feed-in law in place (the 100,000 roofs program stopped almost a decade ago), the playing ground is more leveled for the different PV technologies, creating doubts as to what PV technology will become dominant in the future.

For the Netherlands several useful insights have been gained from the study which can be translated into policy recommendations. First, the Netherlands should ensure that market incentives support the strong aspects of R&D in the Netherlands. In Germany this was initially not done for thin film technologies, leading to growing knowledge base but for a long time no relevant market developments, hampering further growth of the thin film PV sector. Second, demonstration projects should be initiated in the Netherlands early on for promising PV technologies, even if they are not yet in the stage of market introduction. Through this the new upcoming PV (e.g. organic PV) technology will have references of its use which will create less uncertainty for future investors, and potential applications of the technology are shown. Third, the Netherlands should strike a balance between focusing on novel and promising PV technologies on the one hand, and utilizing the established PV technologies on the other hand to sustain interest in PV technology in general, achieve short term goals and keep up expectations. Fourth, the non-continuous nature of Dutch policy regarding PV should not lead to inconsistent policy regarding the different PV technologies. This in order to avoid that a certain PV technology and its innovation system are built up only to be broken down later by policy which favors another PV technology.

Glossary

A-Si: Amorphous silicon
C-Si: crystalline silicon
CdTe: Cadmium telluride
CIS: Copper indium diselinide
CIGS: Copper indium gallium diselide
CI(G)S: Copper indium (Gallium) diselinide
FIS: Function of Innovation System
GWh: Giga Watt Hour
GaAs: Gallium Arsenide
GW: Giga Watt
IS: Innovation System
KW: Kilo Watt
KWh: Kilo Watt Hour
KWp: Kilo Watt Peak
MW: Mega Watt
MWh: Mega Watt Hour
OPV: organic photovoltaics
PV: Photovoltaic
R&D: Research and Development
RGS: Ribbon Growth on Substrate
SSI: Sectoral System of Innovation
STP: Science and Technology Push
TCO: Transparent Conductive Oxide
TF-Si: Thin film Silicon
TSIS: Technology Specific Innovation System
W: Watt
Wp: Watt peak

1. Introduction

Over the past years, a near consensus has been reached that there is a climate problem, and that renewable energy technologies are a vital part of the solution. These renewable energy technologies come in many forms, and certainly one of the most promising of these is photovoltaic technology. Photovoltaic technologies, also known as solar cells, have a number of advantages over technologies that utilize fossil fuels. Of the main advantages is that the sun provides a (practically) endless source of energy and that this energy is clean. However, there are obstacles for widespread diffusion of solar cells. Some of those obstacles are technology related, such as the high upfront investment costs for PV systems. More importantly, it is now recognized that successful innovation is not only a matter of technology; the social context surrounding the technology also plays an important role in successful innovation. Due to the developed PV market, Germany is well suited for a case study in this regard. The German PV market is one of the largest markets in the world, and Germany is a leading country in terms of installed PV capacity. The actual diffusion of PV technology experienced accelerated growth in Germany not immediately after its introduction; instead, generally speaking periods before and after this acceleration in diffusion (also called "boom") can be distinguished, each period with its own characteristic innovation system.

1.1 Research Problem & Goal

It is generally accepted that a sustainable future partly depends on the successful implementation of sustainable energy technologies. There are however stark differences in the rate of success of sustainable energy technologies in different countries. One outstanding example relevant to this thesis is the case of solar cells in Germany. In 2010 in Germany the total PV peak power capacity installed in was 17,320 MWp, compared to, for example, only 97 MWp in the Netherlands (Eurobserver, 2011). It might be argued that Germany is a larger country than the Netherlands, however the figures are still disproportionate: The number of inhabitants in Germany is only roughly 5 times larger than in the Netherlands, while the total installed PV capacity in Germany is almost 200 times higher than in the Netherlands. This shows that the German innovation system apparently was more able to diffuse and develop PV technology. Nonetheless, even the share of PV generated electricity in Germany is still relatively small and comes down to only about 3% of total electricity supply (Reuters, 2011). Thus further development and diffusion of PV technology is needed for a sustainable future, and insight must be gained in to how this can be achieved. Development is necessary due to that fact that PV technologies need to improve to become more competitive with traditional non sustainable energy sources, and diffusion is needed in order to increase the share of PV generated electricity, thereby contributing to a sustainable energy household.

Due to the fact that PV technology in general is still emerging in society (to what extent differs per country), it is in many cases still possible to influence the path of development of the technology. Of course, this applies less to Germany than it does to the Netherlands, due to the fact that in Germany the infrastructure in which PV technologies are embedded is much more developed. At the same time, this offers the opportunity for a country in which PV technology is less embedded and diffused such as the Netherlands to learn from the development and diffusion of PV technology in Germany. Given the fact that factors early in the developments and diffusion of an emerging technology can greatly influence the later outcome of technology and societal context, it is necessary to study the development and diffusion of PV technology *over time*.

But not only is there a difference in diffusion of PV technology amongst countries. An important consideration here is that PV technology does not represent one technology, but rather represents several different technologies that share common principles, the most important of which is the ability to convert sunlight into electricity. There is a significant difference in diffusion amongst different PV technologies. For example, in Germany crystalline silicon solar cells (c-Si) are by far dominant over other (thin film) PV technologies in terms of installed capacity, as will be elaborated on later in this thesis. Furthermore, these different PV technologies are positioned quite differently in the societal context in some important ways, for example in their economic feasibility for certain applications. This points to the fact that a generic understanding and generic policy is not suitable when it comes to the diffusion of PV technology. In order for policy regarding PV technology to be effective, it is essential that a distinction is made between the different PV technologies, so that the different processes contributing to the development and diffusion of PV can be better aligned. Therefore, any lessons learned from the German case must also take into account the different PV technologies, instead of a generic approach.

But the question then remains, what kind of dynamics can occur with different PV technologies coexisting and developing over time, and what issues should get attention when making policy regarding the diffusion of different PV technologies? Up front it is possible to come up with some of those issues, but potentially a lot can be learned from history as well; and Germany with its broad history of diffusion of different PV technologies provides a rich source of information and lessons for policy makers in a country such as the Netherlands where PV is still much less diffused. A comprehensive study of the dynamics of PV technology development in Germany differentiating between the different PV technologies is however absent, and this thesis aims to shed light on the development of the different PV technologies and the relevant contextual factors in Germany over time. In order to reach this, next to considering the development of these technologies individually, it must also be investigated how these technologies were developing and diffusing respective of each other, which will be called competition in this thesis. This necessary, because if a certain factor is causing one PV technology to develop and diffuse much more than another PV technology, the door is opened to misalignment of policy and targets. For example, it could be that a government is focussing its R&D funding on a technology of which it thinks that it is the most desirable technology on the short term, while the same government just launched a market incentive for PV technology in general, but which implicitly favours a completely different PV technology.

1.2 Research questions

In order to reach what has been described in the previous sectionThe main research question in this thesis thus becomes:

How did the different PV technologies develop, diffuse and compete in Germany between 1950-2012?

With the following sub questions to be answered (all to be seen in the light of the main research question):

1. How did the different PV technologies develop and diffuse prior to the period of rapid diffusion?

This sub-question seeks to understand how the situation just prior to the start of rapid diffusion came into being. This is necessary, because one of the goals of this thesis as mentioned in section 1.1 is to draw lessons from the developments in Germany applicable to Dutch policy. Since the Netherlands is still in an early stage in terms of diffusion of PV technology, it is hoped that with these lessons the Netherlands can steer towards a better starting position when rapid diffusion starts.

2. What factors led to the accelerated diffusion
   It is necessary to know and understand these factors in order to be able to understand the subsequent development and diffusion of the different PV technologies, see next question.
3. How did these factors influence the development and diffusion of the different PV technologies?
   Insight must be gained into how the development and diffusion came about for the different PV technologies in order to be able to compare these developments and in order to analyze competition, see next question.
4. How did the different PV technologies compete?
   Insight in competition regarding the factors causing development and diffusion of PV technologies must be gained in order to be able to prevent ineffective policy, see next question.
5. What lessons can be learned for the Netherlands?
   This question transforms the answers to the earlier sub questions into useable recommendations for the Netherlands, and it also illustrates how the understanding and methodology regarding competition used in this thesis can lead to practical recommendations if the specific situation of the Netherlands is taken into account.

1.3 General Principles of PV technology

Photovoltaic solar power generation is based on the direct utilization of incoming solar radiation. This happens in so called solar cells, where light is directly converted into electricity, which is based on the photovoltaic effect. This means that in response to incoming solar radiation, a potential difference is generated at the junction of two different materials (Zeman, 2011). Note that this is different from solar collectors, which basically accumulate heat. The just described process is basically achieved by three steps:

1. Photons are absorbed into the material which generate charged carriers

2. The generated charge carriers in the junction are separated

3. The generated charge carriers are collected in the junctions' terminals.

A schematic representation is given in figure 1.1.

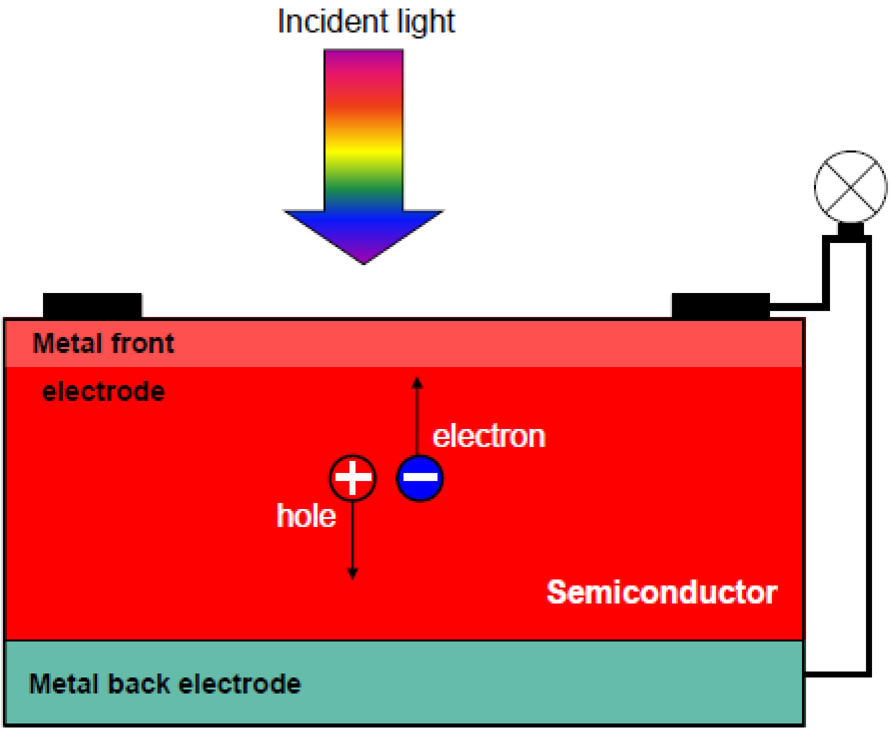


Figure 1.1: A basic schematic representation of the operational principles of a solar cell (Zeman, 2011).

The basic processes are the same for the different PV technologies currently in the market.

1.4 Investigated technologies

The technologies that will be investigated in this thesis are the c-Si wafer technology, as well as thin film technologies such as a-Si, CIS, and CdTe, and organic PV.

1.5 Policy implications

The content of this thesis provides insight into the diffusion of the different PV technologies over time, as well as the relation between the diffusion and the functioning of the different functions in the innovation system (see section 4.4), as well as competition in this perspective between the different PV technologies. Such a study can provide policy makers in relevant fields in Germany as well as other countries with useful knowledge on topics such as:

- What can be the disadvantages of generic policy for different PV technologies?
- What should be taken into account when making policy for different PV technologies?
- How can different factors contributing to development and diffusion of PV be aligned?

These and other topics are very relevant for policy makers in the transition towards a renewable energy household, and the case study at hand provides insight in this through a case study of a country leading in experience and installed PV systems worldwide. Policy recommendations will be formulated towards the end of the thesis specifically for the Netherlands.

This thesis also contains useful information from the perspective of the firm and non-profit organizations, in that it shows the importance of different functions in different contexts, which can be used to lobby more effectively.

1.6 Scientific relevance

The research described in this thesis is unique in that it not only studies PV technology in Germany in a general sense, but makes distinction between the different PV technologies and analyzes competition, which has not been done before except by a few authors, e.g. Kamp & Prent (2009). Studies of innovation systems or related fields up till now for the German PV market did not make any explicit distinction between the different PV technologies (e.g. see Jacobsson & Lauber (2004), or Vasseur & Kemp (2011)), and treated PV as a generic concept. This however ignores many relevant aspects, as there are different PV technologies which must be distinguished in order for the innovation system to be steered effectively. This study therefore sheds light on mechanisms that occur when different technological alternatives are available which are nonetheless often treated as a generic concept, through a case study of Germany.

Furthermore, the research described in this thesis is undertaken through using a particular framework. Thus, the case study that was conducted provides further confirmation/grounds for adjustment of this framework and gives insight into specific issues regarding these functions that can indicate how these functions can be adjusted in the case of PV.

1.7 Structure of this thesis

The structure of this thesis is as follows: The next section will give a global historical overview of the development of PV and its markets. In the third chapter, it will be outlined why the functions of innovation systems approach was used for this case study. In chapter 4 to 11, the functions in the innovation system of the different PV technologies in the different periods will be analyzed, and in chapter 12 the competition between the different PV technologies will be analyzed. The thesis will be concluded and discussed in the chapters 13 and 14.

2. Methodology

In this thesis the development of the diffusion and functioning of the innovation system of the different PV technologies over time is studied as well as competition between them. Thus there are two main parts to the research, although they definitely overlap.

2.1 Functional analysis

With regard to the diffusion and the functioning of the innovation system, this will be investigated by using the seven functions in the functions of innovation systems approach, which will be elaborated on in the theory section in chapter four. By assessing these functions, the functioning of the innovations systems as a whole can be assessed, and insight can be gained into the diffusion of the different PV technologies. In order to assess the different functions, indicators were used which will be described in the theory section. Data for the indicators was taken from sources such as scientific journals, newspapers, books, company websites and a database (e.g. IEA Database) with relevant information on budgets and the like. From these sources information on the different indicators could be extracted. Also Scopus was used for analysis purposes, alongside for finding papers. More specific information on the methodology regarding relevant factors/aspects under study will now be given. It will become more clear in the fourth section in what framework this information should be viewed.

Entrepreneurial activities

With regard to firms/ firm activities, these were more difficult to track for the earliest periods under study. Insight in these periods could be gained through news articles, research articles and patent databases, where indications of entrepreneurial activities were found. In later periods this was easier, due to the presence of lists of companies per sector on the internet, as well as databases of projects. The analysis was mostly of a qualitative nature, i.e. to see if and what kind of activities took place and to what extent, based on the number of companies, their activities and so on. Through this it will be clear if knowledge was transformed into business.

Learning

With regard to learning activities, these are divided in three types. *Learning by searching (R&D)* was investigated through analyzing through Scopus the development of the number of articles on different PV technologies, which could be easily represented over time, and the data could be analyzed using excel. This was used as an indication of trends in R&D in different PV technologies. Furthermore, popular topics in R&D in different time periods could be identified, which was used as an indicator for technology development. Also relevant players in R&D could be identified through Scopus, as well as their collaborations. In order for the previous, and any comparison between data on different PV technologies, to be meaningful, it was necessary that the search for papers on the different PV technologies were comprehensive and exclusive at the same time. For example, in order to find the development of the number of papers on PV technology A, it is necessary that the search 1) finds most relevant papers on the topic 2) does not include a significant amount of papers on other topics. Although a perfect search is practically impossible, since 1) not all relevant papers will fit the search description, and 2) some unwanted papers will be included in the search results, a good approximation was achieved through searching with different queries, and comparing the results, and through looking up all papers from an institute in a given time period, and see if the papers on PV were included in the search results. With regard to *Learning by doing*, this was investigated through looking for developments of price reductions of PV technologies, as well as reading reports that speak about learning from pilot production and so on. Furthermore, the amount of production per PV technology could be found from reports, from which relative learning by doing could be deduced (e.g. the more production for a certain PV technology, the more learning by doing will take place in comparison with another PV technology). With regard to learning by using, reports on pilot applications were found as well as reports describing knowledge related to the application of PV technologies. Such reports provide insight in how much was learned regarding the application of the different PV technologies, which is necessary to understand the development and diffusion of these different PV technologies.

Knowledge diffusion

With regard to knowledge diffusion, collaborations between institutes were searched through scientific articles. This was possible due to the fact that such articles mention the institutes involved in the research. Up to a limited extent it was also investigated around what topics such collaborations take place. Furthermore, collaborations through formalized structures was investigated, such as R&D projects involving different institutes as well as conferences and journals. The analysis focused on whether or not such activities and projects took place, and to a limited extent also their content, e.g. what were differences between different PV technologies here.

Guidance of search

With regard to the guidance of search function, information regarding targets and goals, and support for this, was found through government documents, secondary sources on the topic and so on. Information regarding expectations for the market and technological expectations, this information was found partly through summarized material on government or EU documents describing such expectations, and also expectations expressed in research articles were considered.

Market formation

For the market formation function, information was gathered through secondary sources such as articles and books about market incentives, and market size information was found through government publication and secondary sources. This information was considered in interrelation to each other, i.e. market incentives were described alongside the market growth.

Mobilization of resources

Regarding the function of mobilization of resources, information on the availability of different resources was investigated through government (related) publications as well as statements from industry players.

Advocacy coalitions

The function of advocacy coalitions was analyzed through secondary sources such as books, but also first-hand accounts from relevant players (from written material). The advocacy coalitions themselves as well as their activities and results from these activities could be identified through this, as well as the effect on the technology in a broad sense.

2.2 Categorization of phases

The data that was gathered for this part of the study was categorized into a set of phases, in order to give more structure to the vast set of gathered data, and in order to understand the differences between certain periods in terms of functioning of the innovation system. The phases were divided by a global study of the diffusion of PV in Germany, which gave an initial idea of the phases. Subsequently different studies were investigated and it turned out that the phases used in these studies were roughly equivalent to each other, but also to the initially identified phases. This is in part due to the clear temporal distinction of relevant policy programs (e.g. policy program A from year W to year X, policy program B from year Y to year Z, etc.). Since these policy programs had great influence on the diffusion of PV in Germany and the functions in the innovation system, they were well suited in determining the different phases of development. However, this is true insofar as PV is considered in general. If a distinction is made between the different PV technologies, it becomes clear that the different PV technologies show some differences with regard to the phases. For example, the established c-Si PV technology experienced large scale diffusion at some point, but this was not the case for other thin film technologies. Nonetheless, it was deemed more appropriate to stick to the general classification of the phases for the following reasons:

1. Although there were differences between the PV technologies in terms of the functions in the different phases (e.g. in terms of market size), there were also commonalities (e.g. rise in entrepreneurial activitities) in the various phases between the different PV technologies.
2. The phases are mostly based on policy initiatives that were not directly targeted at any particular PV technology (although indirectly they did make a distinction between the different PV technologies).
3. Phasing was considered necessary in order to analyze the competition between the different PV technologies (i.e. without such phasing comparison is difficult between the function of the innovation systems of the different PV technologies), and the phasing thus had to be as comprehensive as possible, as well as the criteria. Phasing on the basis of (mostly) policy initiatives suits this best.

The following categorization of phases is used:

1970-1985: PV energy in this period was still an extremely expensive form of renewable energy. Nonetheless the issue became more important due to the oil crises which increased the drive of the German government to become less dependent on fossil fuels. Research on PV was therefore supported by the government. Support for the diffusion of PV was not relevant at this time due to the high costs which had to be decreased through more R&D. The issue at this time was thus more one of technology than society.

1986-1991: The start of this period is marked by the Chernobyl nuclear disaster, which increased the pressure for alternative forms of energy for nuclear energy, and in particular PV energy. Thus the amount of R&D funding went up from 1986.

1991-1994: At the beginning of this period the 1000 roofs program started. Although this program had a small direct impact on the diffusion of PV, it did have an important impact on the PV sector itself (e.g. expectations, new institutes) as well as on the contextual environment (e.g. grid connection which was now ensured).

1994-1998: This period starts with the end of the 1000 roofs program, and represents a sort of intermediate period with a lacking growth. Even though there was no direct follow up program, the prospects of a follow up program that was to come (the 100.000 roofs program) did seem to have generated some activity.

1999-2003: At this point in time the 100.000 roofs program started, which proved to be a vital program for the diffusion and development of PV. Not only did this program start, but also the EEG feed in law which would, together with the 100.000 roofs program, make PV an economically feasible option for the first time.

2004-2012: This period starts when the 100.000 roofs program ends. This implied a lack of funding for the PV sector, which was subsequently compensated in 2004 by an adjustment of the EEG act which led to a further increase in the diffusion of PV as well as research activities until today.

A similar phasing was suggested by Bruns et al. (2011) and Jacobsson and Lauber (2004), although the details somewhat differ. Table 2.1 briefly shows the differences.

Table 2.1: Phases of development of the diffusion of PV in Germany according to Bruns et al. (2011) and Jacobsson and Lauber (2004).

	1970-1975	1975-1980	1980-1985	1985-1990	1990-1995	1995-2000	2000-2005	2005-2010
Bruns et al.	Pioneering phase			Decline industr. & R&D	Large scale testing	Uncertainty, Slow down	Breakthrough.	Boom in development
Jacobsson et al.		Formative phase for wind and solar power			Take off for wind, not for solar		Take off for solar power	

2.3 Competition analysis

In order to analyze the competition between the different PV technologies, it was necessary first to get make clear how competition is to be understood in this case study. Competition in a generic sense means that two or more different things compete for the same goal/resource and that achievement of the goal of one thing will negatively affect the other thing in terms of achievement of the goal/resource. Of course the PV technologies under study in this thesis cannot compete in the sense of the meaning given above. Competition in this thesis is understood in that the functioning of a function A within the innovation system of PV technology B will have a negative or blocking effect for the functioning of function A for other PV technologies C, D, and so on. The reason for choosing this understanding of competition, and studying it in this sense, will now be outlined.

First, the functions of innovation systems approach (see section 4.4) with the mentioned functions assumes that these functions are a comprehensive and vital set of functions which need to function in order for the innovation system to be able to diffuse and develop the technology. For clarification, I will now consider the hypothetical situation, that the functioning of function A within the innovation system of PV technology B can negatively influence or block the functioning of function A within the innovation system of PV technologies C and D. For example, consider the situation that the (sub)function learning by searching for PV technology B is fulfilled at the cost of the functioning of learning by searching for PV technology C and D. This means that the mechanisms (for example policy and funding) causing learning by searching for PV technology B must be identified, and evaluated, because now there is the risk of these mechanisms being ineffective; it could well be that these mechanisms were originally intended to lead to learning by searching for all PV technologies, or another PV technology. And, it could be that another function E (e.g. entrepreneurial activities) is working in the favor of PV technology C at the cost of B, while function A (learning by searching) is benefitting PV technology B much more than C. This possibly leads to a growing knowledge base for PV technology B at cost of PV technology C which does not get to the market through entrepreneurial activities, as these favor PV technology C . In other words, mechanisms which were intended to enhance the functioning of the innovation system are at risk of being ineffective in those areas where competition (as understood in this thesis) takes place. This is because in these areas of competition, the PV technologies cannot all benefit from the function at the same time without that hampering or blocking the function for other PV technologies, because by definition in these areas of competition, more for one PV technology means less for the other. This implies in turn that if competition exists in some functions, the functioning of the innovation systems of the PV technologies *can never* be ideal for all PV technologies at the same time. In such a function where competition takes place, its functioning will be stronger for one function and inevitably weaker for another function. It is necessary to know then such functions where this competition takes place, because we then know that if we want to enhance such functions (e.g. function A and E) for PV technologies B and C, we are at risk of enhancing a function A for PV technology B but not for PV technology C, while function E is enhanced for PV technology C but not for B. If we assume that function A and E are both necessary functions that must be enhanced, the enhancing of the functions has been ineffective and will not lead to the desired result. Thus, the understanding of competition described here allows me to find those areas that need extra attention when trying to steer development and diffusion.

General analyses on PV technology could indicate growing diffusion, while under the surface this growth turns out to be unnecessarily limited due to misalignment of underlying mechanisms. An analysis of competition identifies areas where this could happen, and also *how* this misalignment comes about, which is necessary to solve the misalignment. How this understanding can be translated into research methodology is now discussed.

It is necessary first to identify in which areas (i.e. functions, see section 4.4) competition takes place. This was done through the following two steps:

1. Compare the outcomes of the individual analyses of the different PV technologies, based on the different indicators (see 4.4.) studied.
2. Assess per function if competition took place, i.e. if functioning for one PV technology implied decline or blocking in functioning for another PV technology

Per function, this meant the following:

Function 1: Entrepreneurial activities

It was analyzed whether or not an increase of firms regarding one PV technology hampered the increase of firms for another and if an increase in (entrepreneurial) activity for one PV technology implied a decrease for such activity for another PV technology. This was done through analyzing firm activities over time and how these firms divided their entrepreneurial attention between the different technologies.

Function 2: Knowledge development

It was analyzed whether or not the increase in (research) papers for one PV technology led to a decrease of research papers for another PV technology, how funding was divided between the different PV technologies, comparing learning by doing for the different technologies in terms of production, and comparing learning by using in terms of demonstration projects and installed capacity. The just mentioned factors are factors in which a tradeoff must be made (e.g. more attention for R&D in one PV technology means that that extra attention cannot be given to R&D in another PV technology), and as such they are embody the meaning of competition given in this thesis.

Function 3: Knowledge development

Regarding this function, it was analyzed whether knowledge diffusion activities such as collaborations and presentations at conferences for one PV technology took place at the expense of another PV technology.

Function 4: Guidance of search

Here the information for the indicators from the different PV technologies was compared. Thus, expectations of market and technological developments were assessed for the different technologies, as well as government support for guidance of search for the different functions and the different targets. This, however, did not necessarily reveal competition, as a necessary condition for competition for a function's benefit is that more technologies cannot attain the same benefit of that function except at the expense of each other. Whether this was the case was determined by analyzing the indicator on whether or not PV technologies had to fight for the same factors represented by the indicators. For example, financial support for R&D goals is limited and a tradeoff must be made between supporting different PV technologies.

Function 5: Market formation

For this function market size developments for the different PV technologies were assessed and compared, as well as market formation incentives and their respective effects on the different PV technologies and their markets. The reason is that with these aspects there is practically limited opportunity to benefit from them (e.g. market share must be divided amongst PV technologies), and a growth for one PV technology can mean decline for another PV technology (but this is not necessarily so, for example if different market segments use different technologies). Regarding market incentives in any case there is a limit, as the government or relevant institutions can only provide limited financial resources that are needed for these market incentives.

Function 6: Mobilization of resources

In order to analyze competition in this regard, it was assessed whether or not the resources were available to one PV technology at the exclusion of others, and how this was distributed in practice. This was done through first analyzing the type of resource and whether or not competition can logically take place in this regard (e.g. if two PV technologies use entirely different raw materials, there is no competition regarding the resource raw materials). If this was the case, the distribution of resources was investigated between the different PV technologies.

Function 7: Advocacy coalitions

For this function the activities were analyzed with regard to if they focused on a specific PV technology at the expense of another. Also the outcome of the activities of the coalitions were assessed in terms of their consequences for the different PV technologies. This relates to competition in the sense that advocacy coalitions can only cover a limited amount of topics, and the effects of advocacy coalitions can be limited to certain PV technologies to the exclusion of others, although this is not necessarily the case. Whether or not this was the case was investigated by finding out the outcomes of those advocacy coalitions (e.g. a policy program), and subsequently investigating whether these outcomes favored a particular PV technology at the expense of others.

Then the third step was carried out:

3. Analyze causes and consequences of competition.
   This step is necessary in order to come up with recommendations for policy for the Netherlands. Such recommendations have the goal of steering the development of the PV technologies into the desirable direction, where the development of the different PV technologies is aligned. Steering can only be done if it is know what underlying mechanisms should be influenced (the causes), as well as what such changes can and cannot lead to (the consequences).

Also important forms of indirect competition were identified. This means that not always were PV technologies directly competition for a certain resource, but rather were favored (or “naturally selected”) over others, thus in a passive way. This happens for example when a certain market incentive is not explicitly of directly targeted towards a certain PV technology, but only one PV technology happens to fit the conditions for growth under the market incentive.

3. Historical global overview of PV

The photovoltaic effect was first observed by Becquerel in 1839. The first conventional PV cells were manufactured towards the end of the 50'ies. The application of solar cells at this time was mostly for space applications (satellites). The costs of a PV system were still very high and nowhere near suitable for the terrestrial market. However, because the cost of the PV system was not a determining factor for space missions, PV cells were a very suitable way of generating electricity for satellites in space. As the field of PV further developed, the quality, performance and manufacturing process were improved which opened up possibilities for other terrestrial market segments beside space applications. This was mainly in applications such as battery chargers for navigational equipment, signals and telecommunications equipment as well as other vital equipment with a low energy use (FSEC, 2012).

In the 70'ies energy crises occurred, which triggered developments towards the use of PV in residential and commercial applications. In the 80'ies, PV was increasingly used in commercial applications such as calculators, watches and so on.

Off grid applications were important in terms of market size in the 90'ies (e.g. in remote industrial applications) as can be seen in figure 3.1. However, due to the support programs in countries such as Germany, Japan and the US, the market for grid connected PV became larger than the market for off grid PV around 1999 as can be seen in figure 3.1. Thus a shift took place in terms of the weight of market segments. In this period, the growth of the global PV market was about 33%, and the global PV market had reached a size of about 450 MWp in 2002, and 400 MWp in 2003 (Hoffmann, 2005).

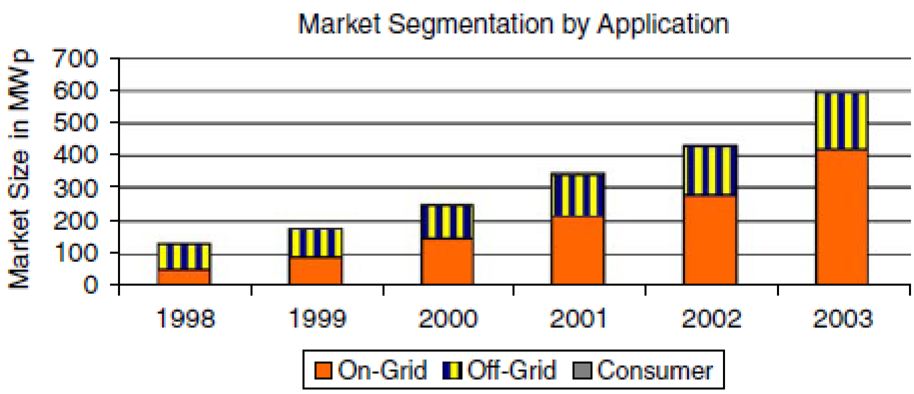


Figure 3.1: Global growth of different market segments in PV market from 1998 to 2003 (Hoffmann, 2005).

The growth of the worldwide PV capacity from 1995 to 2009 is shown in figure 3.2.

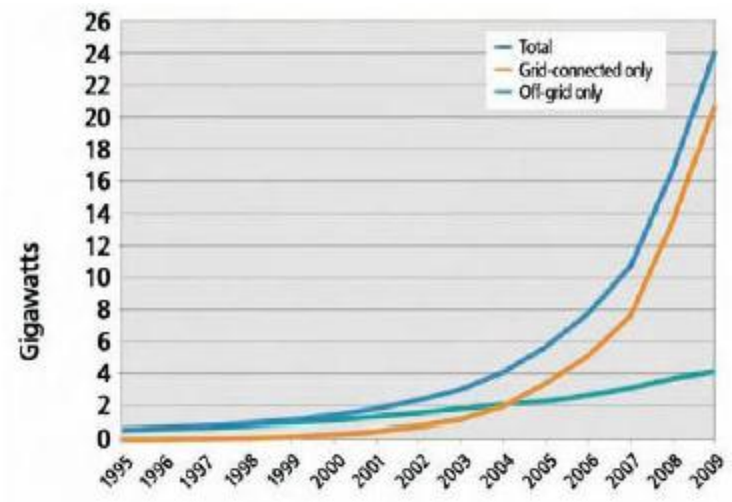
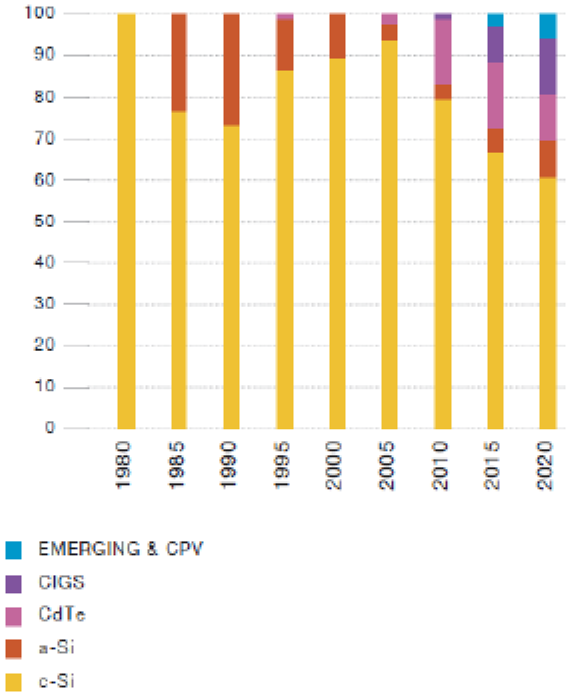


Figure 3.2: Development of worldwide PV capacity installed in 1995-2009 (REN21, 2010).

In recent times, the global PV market is growing with about 25% annually, and programs have been implemented in Japan, the US and Europe, which is further stimulating the diffusion of grid connected PV systems (FSEC, 2012). The quick growth of the PV market however should not lead on to think that the share of PV in electricity supply is at a high level: Only 0,1% of the electricity globally is produced through PV technology.

When speaking about the PV market, it must be taken into account that there are multiple PV technologies. The distribution of market share amongst these technologies has not been static over the years, as can be seen in figure 3.3. While c-Si PV technology started off as having almost the exclusive market, this changed and other (thin film) technological PV alternatives were developed. Nonetheless, c-Si PV technology remains dominant although its dominance is expected to weaken in the future as can also be seen in figure 3.3.



Figuur 3.3: Development of market shares of different PV technologies over time (EPIA, 2011).

There are also other (organic) PV technologies emerging, which have not been established in the PV market yet and require more R&D.

The distribution of PV capacity amongst countries is very unevenly balanced across the globe, as can be seen in figure 3.4.

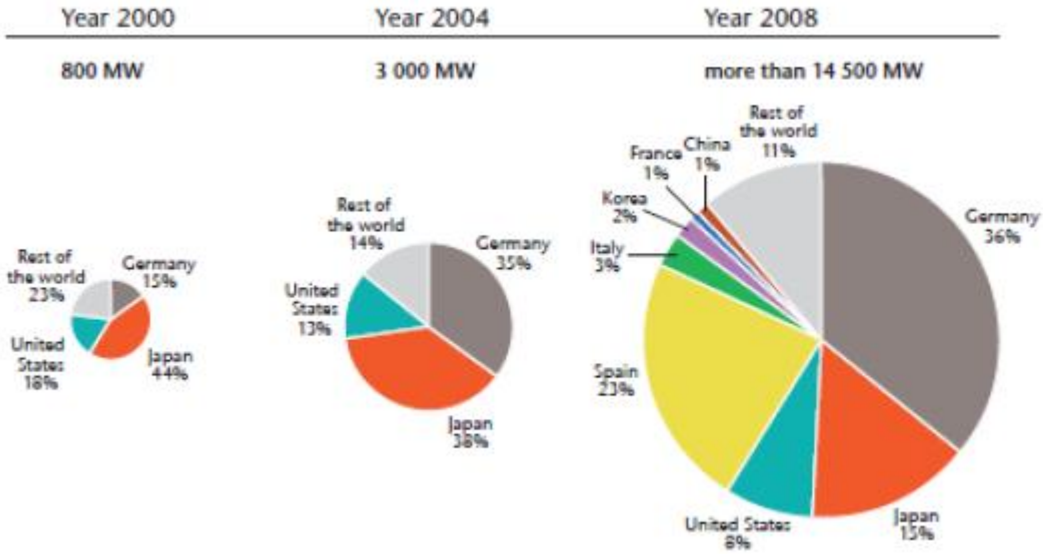


Figure 3.4: Shares of installed PV capacity amongst different countries (IEA, 2010).

This is largely caused by policy incentives, of which the German version will be discussed later on in this thesis.

4. Theoretical framework

In this section various theoretical models will be shortly discussed that relate to the subject studied in this thesis. Then the motivation will be given for choosing a particular framework among these frameworks.

These theoretical models mainly take a systems approach to innovation. Innovation can be described as "*technologically novel or improved material goods, intangible services or ways of producing goods and services*" , and sustainable energy technologies are recognized to be a form of innovation (Coenen & Diaz Lopez, 2009). In todays' society, innovation is not the result of the work of an individual or an organization, nor is it a singular event; instead a network of different parties is involved in an iterative process (Coenen & Diaz Lopez, 2009). This understanding of how innovation takes place gives rise to the systems approach to innovation.

In order to make a study of the system possible, the system must be delineated in terms of its components and boundaries, and the system boundaries must be determined. This is done by determining what organizations and institutions shape innovation and technology development (Coenen & Diaz Lopez, 2009). Different criteria have been used in order to do this, which globally explains the differences between the system approaches explained now.

4.1 National Systems of Innovation

This framework partly emerged from the criticism on economists of not integrating institutions in theories/models and is one of the first frameworks after the linear innovation model(**Godin, 2007**). The National Innovation System is defined as follows: "a set of institutions whose interactions determine the innovative performance of national firms" (**Nelson, 1993**). The goal of the R&D system according to this framework is innovation, and this system is in itself part of a larger system including government, industry, universities etc. (Godin, 2007). A central characteristic of a National Innovation System is the way knowledge distribution takes place, as well as how the knowledge is used; thus the interaction and relationship between the different entities within the NIS are crucial in this framework and indeed seen as vital in explaining the performance of the NIS (**Godin, 2007**). All of this should be viewed within national borders of the NIS. It is therefore not surprising that advocators of this framework hold that the aspects in the innovation system specific to the nation are what mostly determines the development and diffusion of innovation within a country.

4.2 Sectoral Innovation Systems

The Sectoral System of Innovation is defined by Malerba (2004) as follows: *"sectoral system of innovation and production is composed of a set of new and established products for specific uses, and a set of agents carrying out activities and market and non-market interactions for the creation, production and sale of those products"*. Thus, in the Sectoral Innovation Systems view, innovation is mainly viewed as a way for firms/industries to be competitive, and the firm is seen as the main unit responsible for innovation (Coenen & Diaz Lopez, 2009).

In this framework the focus is on groups of networks of enterprises (i.e. sectors) and a dynamic view of these sectors. A Sectoral System of Innovation can transcend geographical borders and can include more than one technology (Coenen & Diaz Lopez, 2009). As boundaries are emphasized on the basis of existing product groups (e.g. chemicals), it can prove to be difficult in the SSI approach to set boundaries for emerging (sustainable energy) technologies, including PV technologies (Coenen & Diaz Lopez, 2009).

According to this view, firms are connected to each other in two ways: Through processes of interaction and coordination in development and production of technology, and through processes of competition and selection in innovation and market activities (Pierick & van Mil, 2009). Mutual knowledge exchange and knowledge spillovers are core elements of this framework. It is therefore not surprising that the SSI is not independent of what happens at a national level in a national innovation system in which part of the SSI is located, as national activities influence what has just been described. A National Innovation System is also influenced by a SSI, due to the fact that the national system covers multiple sectors of innovation that influence the activities in the NIS.

4.3 Multi-Level Perspective

This perspective offers a conceptual framework which explains transitions in socio-technical systems on the basis of processes on different levels, starting at the lowest (micro level) up until the highest (macro) level (Pierick & van Mil, 2009). Social and institutional learning are key in such transitions and long term processes (Coenen & Diaz Lopez, 2009). It is the result of an attempt to gain more insight in large scale socio-technical change, or regime shifts, and why and how these come about (Pierick & van Mil, 2009). While the innovation system approaches offer key insights regarding the functioning of systems, these approaches offer less insight in the transition from one system to another system, while the Multi-Level Perspective does allow for more study on this (Geels, 2005). For example, in the MLP approach it can be studied how a new sectoral innovation system emerges and how it is linked with the previous sectoral innovation system (Geels, 2005). This is done through the conceptualization of different levels.

The micro level is the niche level where new technological variation emerges. At this level there is not much stability and much uncertainty (Geels, 2005). One of the vital functions of a niche is that learning processes take place in different ways, such as technological and infrastructural (Geels, 2005).

The meso level is the level of the regime, which refers to: "the rule-set or grammar embedded in a complex of engineering practices, production process Technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems - all of them embedded in institutions and infrastructures" (**Rip en Kemp, 1998**). Thus rules in this perspective do not only relate to technological matters, but also to social aspects, and they can be embedded in social structures also. In such regimes, lock-in and path-dependency is created by existing institutional frameworks (Coenen & Diaz Lopez, 2009). On the level of niches it is possible to deviate from the rules in the incumbent regime, and thus the niche is the level where new paths and innovation emerge (Coenen & Diaz Lopez, 2009).

The macro level is the landscape level which forms the background on which developments at the micro and meso level take place. Developments on the landscape level are not directly a part of the regime and niche, but they do influence these levels. The other way around, i.e. that processes on the regime and niche level influence the landscape, is much more difficult and uncommon.

In can thus be seen that the Multi-Level Perspective offers conceptual comprehensiveness and the focus is on change from a broad societal perspective; however this makes it more difficult to operationalize this approach for empirical research (Coenen & Diaz Lopez, 2009).

4.4 Technology Specific Innovation Systems (TSIS)

Initially, this framework emerged from what known as the concept of Technological Systems. This was defined by Carlsson and Stankiewicz as: *"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). Hekkert and Negro (2008) defined the Technological Innovation System as follows: *"a network or networks of agents interacting in a specific technology area under a particular institutional infrastructure to generate, diffuse, and utilize technology."* This innovation system is a technological system by definition, and clearly includes the possibility that such a system can have national , regional and international borders, as well as the possibility for a technology to cover multiple industrial sectors (Coenen & Diaz Lopez, 2009). In this approach to innovation systems the technology is the point of focus, and the TSIS approach thus makes it possible to use a framework to study the development of actors, networks and institutions over time, as the technology is common to all these in the TSIS approach (Coenen & Diaz Lopez, 2009).

In order for a technology to develop and be widely diffused, it is necessary that the TIS functions well, however this is difficult to determine (Kamp et al., 2009). For this reason, system functions have been identified, which are in essence the factors that influence the functioning of the system as a whole, or in other words the development, diffusion and use of a technology (Kamp et al., 2009).

A function is defined as "a contribution of a component or a set of components to a system's performance" (**Johnson & Jacobsson, 2000**). This approach comes from a functional perspective on innovation systems, i.e. how the system works. In order to compare the performance of innovation systems, an assessment in terms of their functions is necessary (Markard & Truffer, 2008). In a general sense, the functions of the innovation sense can be categorized as the generation, diffusion and use of innovation, however various sub functions have been proposed. Thus, whether or not the system as a whole is functioning, is dependent on the quality of the sub functions, as well as their interaction (Markard & Truffer, 2008). Put differently, the TIS can be analyzed and described in terms of how the functions have been served (Kamp et al., 2009). This is of course under the assumption that the functions are comprehensive. Several sets of sub functions have been proposed, in this thesis the set proposed by Hekkert et al. (2007) will be taken. The seven sub function are as follows:

1. **Entrepreneurial activities**

   Entrepreneurial activities are necessary in order to turn knowledge into business, thereby making use of the potential of the technology. Innovation cannot exist without these entrepreneurial activities.

2. **Knowledge development**

   Innovation cannot take place without the development of knowledge through a number of mechanisms. **Kamp et al. (2004)** identified four separate learning mechanisms: Learning by searching (R&D), learning by doing, learning by using and learning by interaction (which will be discussed in the next function).

3. Knowledge diffusion

This is the function of learning by interacting, which comes down to exchanging knowledge in a network. This is particularly important in a network where government, R&D, competitors and market meet (Kamp et al., 2009).

4. Guidance of search

In order for limited resources to be effective, it is necessary that guidance of search takes place in order to focus resources towards a specific path or paths. This can work through different ways, such as expectations created by a breakthrough technology or government funding (Kamp et al., 2009).

5. Market formation

Due to the fact that new technologies are often not immediately competitive with their established alternatives, it is necessary to give them initial protecting, possibly by creating a temporary niche through subsidies or by a specific technological market where the technology *is* competitive (e.g. which was true in space travel in the case of solar cells) (Kamp et al., 2009).

6. Resources mobilization

Resources are necessary in the innovation system in the form of human, physical and financial resources (Kamp et al., 2009).

7. Creation of legitimacy/advocacy coalitions

Initially a new technology will face opposition from parties with vested interests in the regime, and this resistance necessitates counter resistance in order to create legitimacy (Kamp et al., 2009).

4.5 Justification of framework

If the PV technology and the topic in this thesis is considered, a number of needs emerge which have to be met by the framework that is used for such a study. These criteria are:

Technology specific*: Since the development and diffusion of PV technology is the focus of this research, the framework must allow for technology specific research and the system must be bounded by the technology to avoid studying aspects that do not determine the development and diffusion of PV*

Dynamic analysis: *Due to the fact that development and diffusion of PV technology imply change and are a result of actions and activity, the analysis must incorporate the dynamics of the system in order to explain the diffusion and development of PV technology.*

Relevant institutional infrastructure: *The framework must deal with relevant institutional infrastructure, i.e. whatever institutional infrastructure determines the development and diffusion of PV, and therefore include relevant national infrastructure as this strongly influences development and diffusion of technology.*

Allow for comparison between systems: *As was explained, the comparison of the different PV technologies, their development and innovation systems is a point of focus in this thesis. Therefore the framework should facilitate this, e.g. through categorization on the basis of which comparison can take place of factors that hinder or stimulate the development and diffusion.*

Analysis over time: *Part of the research question to be answered in this thesis covers the past, which is necessary to gain insight in to the emergence of PV technology.*

Links technology to context: *Due to the fact that some contextual differences inevitably have their origin in the physical technology itself (e.g. certain material is need with high cost, which can lead to higher price and lower market share), it is necessary that the framework gives insight into the relation between the technology and the contextual situation.*

Comprehensive: *The relevant factors that develop and diffuse the technology must be incorporated in the framework, in order to gain a good insight into the determinants*

The criteria and the corresponding suitability of the different frameworks is shown in table 4.1

Table 4.1: Criteria for the framework to be used with corresponding suitability of the different frameworks.

	MLP	NIS	SSI	TSIS
Technology specific	*			*
Dynamic analysis		*	*	*
Relevant institutional infrastructure	*	*		*
Allows for comparison of systems		*	*	*
Comprehensive	*			*
Links technology to context	*			*
Over time analysis	*	*	*	*

With regard to the national systems of innovation approach, in this approach innovation systems are studied on a national level, and it is not technology specific. This includes a large amount of actors, relations and institutions, which makes a focused study of PV technologies and a study of the dynamics of the system difficult to map, and thus authors using this approach usually focus on the structure rather than the dynamics (Hekkert & Negro, 2010). This alone disqualifies the NIS for the purpose of this thesis.

The Sectoral System of Innovation on the other hand is more specific with regard to sector, however it is still too general as only specific energy technologies are under study in this thesis instead of entire product groups. Furthermore national boundaries are important in this thesis, as Germany is the background in which the development and diffusion of PV will be studied. Also, relevant institutional infrastructures are not incorporated in the SSI approach such as governmental departments or activities that influence PV technology development and diffusion, and the technology is not placed in the wider context of society even though this is important in the diffusion of technology.

With regard to the MLP perspective, it can be useful in that it provides a comprehensive view of change, however it is difficult to use in comparing different technologies on a systematic categorized basis, due to the absence of a categorization of relevant factors that determine the development and diffusion of PV technologies. Furthermore, due to the fact that MLP provides such a comprehensive and broad perspective and is very complex, in depth empirical research and comparison regarding the different PV technologies becomes very difficult (Coenen & Diaz Lopez, 2009). Also, the focus in MLP regarding learning is relatively more towards social learning, which is understandable when the focus is understanding larger scale societal transitions. However in the case of PV, such a transition on a societal scale did not yet take place in the period under study, and the focus in this thesis should be more towards learning regarding technologies, as technology is the common denominator between the different PV technologies which can be compared. Also, learning regarding technology was a vital dynamic process that facilitated the development and diffusion of PV, e.g. through price reductions and increases in efficiency.

With regard to the TSIS framework, the PV technology is under study and requires a technology specific framework such as TSIS. Furthermore, the analysis must be comprehensive which requires the analysis of its diffusion to incorporate learning, market formation, advocacy coalitions, etc., as these are essential for an emerging technology. TSIS offers a comprehensive approach through incorporating the relevant functions that need to be in place for the innovation system in order to function. For this reason the TSIS framework is very well suited, as it captures a comprehensive set of functions which are vital for an emerging technology like PV. Furthermore, the FIS framework allows for focus on a specific technology, and on the specific national aspects which are relevant, instead of focus on the whole national innovation system or the whole sector. Another relevant aspect of the topic in this thesis is the competition between different technologies of PV in Germany, which necessitates a basis for comparison of these different PV technologies. In order for the competition to be analyzed, a set of common factors is thus needed which will be analyzed in the light of competition. Furthermore, these factors must capture the dynamics of the system, as competition between different technologies in an emerging field can only be meaningfully analyzed if the change regarding one factor, for one technology, is compared to the change regarding the same factor, for the alternative technology. This is because structures (i.e. the innovation system components) have changed a great deal over time. Thus the framework needs to be comprehensive and cover the relevant factors/processes within the innovation system, be specific for the technology and consider technological as well as social aspects. For this reason and the reasons mentioned earlier, the TIS framework will be used, and the dynamics within the innovation system will be analyzed using the functions of innovation systems (FIS) approach, as it is comprehensive, technology specific, holds for a specific economic area, provides a categorized basis of comparison (i.e. the seven functions) for the different technologies, and allows for analysis of the dynamics and development over time of the innovation system.

4.6 Indicators for the FIS analysis

The indicators used in this thesis are listed in table 4.1, based on the work of Kamp et al. (2009) in a similar study for PV in Japan and in the Netherlands.

Table 4.1: Indicators used in this thesis for the FIS analysis.

Functions	Indicators
Function 1: Entrepreneurial activities	• Type of entrepreneur • Change in the number of entrepreneurs • Recent activities • Future (announced) activities
Function 2: Knowledge development	• Type of organisation performing research • Type of research activities (basic/applied) • Start of national research project • International recognition • Start of production • Production cost changes • Market size indication • Feedback from market
Function 3: Knowledge diffusion through networks	• Collaboration between organisations on R&D • Formalised exchange methods
Function 4: Guidance of the search	• Targets set by government or industry • Type of targets (research/ market/ installation) • Support for goals • Technological expectations • Expected continuation of development and diffusion
Function 5: Market formation	• Market size • Consumer motivation • Financial market incentives

Function 6: Resources mobilisation	• Availability of venture capital • Availability of (research) employees • Availability of specialised education programmes • Availability of raw materials
Function 7: Creation of legitimacy	• Existence of advocacy coalitions • Activities of coalitions • Recent results of activities

5. 1950-1970

5.1 Entrepreneurial activities

Experience with solar cell manufacturing in Germany goes back decades. For example, AEG Telefunken was active since 1958 with developing solar cells for space travel (Schott Solar, 2011). The market at this time was still very limited, and mostly focused on extra-terrestrial applications of solar cells. In 1968, the first satellite with AEG cells was launched (Bruns et al., 2011). In 1964 AEG was already occupied in the basic development of silicon solar cells for terrestrial use, and the production started in 1965 (Schott Solar, 2011).This was however still very expensive. Siemens was also involved in the PV sector in the 1950's; it's first milestone was the production of ultrapure monocrystalline silicon using zonal heating, which is a technology still widely used today (Suppliers-PV, 2011). Prices were still very high, but this did not pose a problem for the space industry. Thus large scale power generation was not what PV was used for historically, nor domestic power generation on a smaller scale.

5.2 Knowledge development

5.2.1 Learning by searching

Silicon

Already in the 50/60'ies research into PV was done by German industry, such as AEG, Wacker Chemie and Siemens (Bruns et al., 2011). Siemens for example introduced a new method for producing ultrapure monocrystalline silicon around the 50'ies, which is called the floating zone method, or zonal heating. This was the basis for most of the future production of ultrapure silicon for the semiconductor industry, but which could also be used for PV cells. The main application of solar cells at this time was for the space industry, and they were exclusively monocrystaline cells (Bruns et al., 2011). In fact, Wacker Chemie was already researching in the area of hyper-pure silicon in 1947. Cost were very high at that time, but this did not pose a problem for the space industry.

6. 1970-1985

6.1 Entrepreneurial activities

Cells & Modules

In the early period few companies were active in the field of silicon PV in Germany. Detailed information from firm activities in this period was difficult to find, however at least AEG en Siemens were active in producing silicon solar modules (Jacobsson & Lauber, 2006). For example, AEG started the series production of PV modules in 1978 through a plant of 20kW per shift (Starr & Palz, 1983). In 1981 AEG was the largest PV manufacturer on the market, however it was likely to face competition as Siemens had a PV manufacturing plant that went operational in 1982 (Starr & Palz, 1983).

With regard to Siemens, by 1981 they had been producing PV modules for some time, but with the cells of other producers (Starr & Palz, 1983). However, with the building of the new facilities mentioned earlier, Siemens decided to have their own silicon and cell production facilities and to extend the capacity for making modules. The plant's capacity was 2MWp/year (Starr & Palz, 1983). Furthermore, Siemens was developing cells for specific applications such as for water pumping systems (Starr & Palz, 1983).

Raw materials: Silicon

In 1978, poly-crystalline blocks were manufactured by Wacker Chemie and AEG-Telefunken through a new method, which now made it possible to mass produce poly-crystalline silicon (with an initial efficiency of 13%) at much lower price than the silicon manufactured through the Czochralski process (Green, 2001). The new technique employs the controllable solidifying of molten silicon, in large columnar grains in a suitable container, upwards from the bottom of the crucible. The multicrystalline wafers manufactured in this way had a performance of about 80% of monocrystalline wafers produced through the Czochralski method (Green, 2001). Wacker furthermore started the production of wafers in 1983, but quitted in 1988 due to a lack of demand at the time (Bruns et al.,2011). This furthermore confirms the infancy stage of the PV market at this point of time.

Activities

In 1983, on the island of Pellworm, Germany's first PV power plant was built with silicon modules from AEG. This demonstration project was entirely funded by the federal government as part of a European pilot program (Jacobsson et al.,2002). Early 1980's, Siemens was involved in a terrestrial project in Greece where monocrystalline cells were installed in a 100 kWp installation. The market in this early period was however still very limited. Due to the high costs, PV was only feasible in particular small niches. Nonetheless, in the second half of the 80'ies the first grid connected application of PV on residential buildings appeared (Bruns et al., 2011).

Thin film

In this period, thin-film solar cells concepts emerged, for example at MBB (Schott Solar, 2011). Information on this development from MBB (this was a German aerospace company) is scarce, however it is known that they were developing a-Si technology. This would be the first commercially mass produced thin-film technology taking up most of the thin film market. Since they were an aerospace company it may be assumed that they did not develop this technology for domestic application, but to incorporate into spacecraft. There was other R&D work going on in laboratories and firms (see knowledge development function), however thin-film related entrepreneurial activities were scarce or absent in this period. This shows that already at this point in time, thin-film cells were lagging behind in commercialization in the field of what would late become the main market: Large scale grid-connected power generation.

6.2 Knowledge development

6.2.1 Learning by searching (R&D)

As a general note, it can be said that R&D on PV cells in this period slowly started to pick up, as is indicated by a search on Scopus for papers (“solar cells”). The development of the number of papers from German origin on PV in this period is shown in figure 6.1.

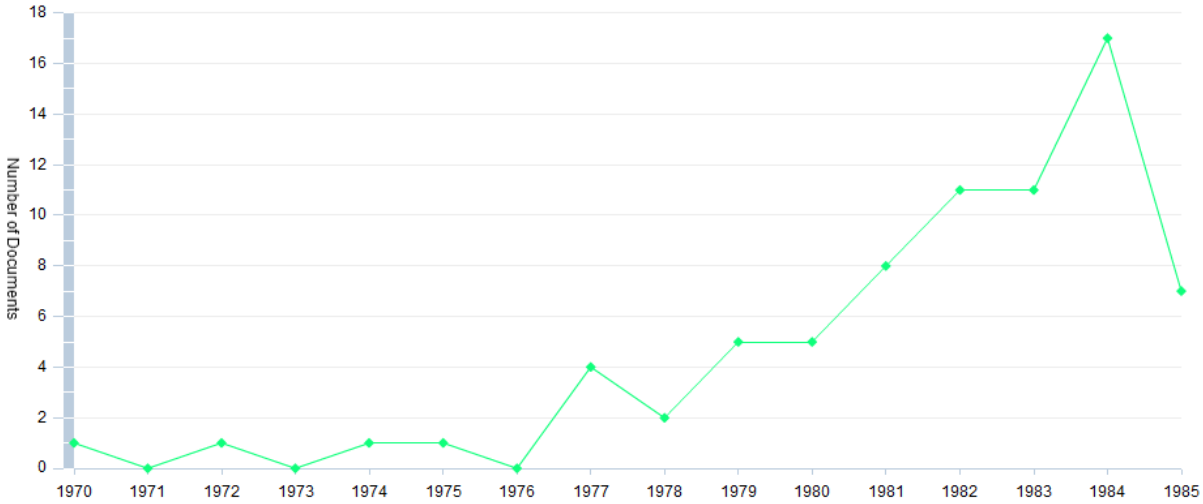


Figure 6.1: Development of the numer of German papers on PV in this period, found through a search on Scopus for “solar cells”.

Silicon

In the 1970’s, oil crises took place which resulted in governmental involvement into renewable energies, as can be seen in table 6.1 which shows public R&D spending on PV. In this period the German government introduced state research funding for PV electricity generation for the domestic sector (Bruns et al. 2011). The support came from the Ministry of Research. The funding was almost exclusively restricted to promotion of research (Lauber & Mez, 2004), development and for a small part also demonstration (Jacobsson & Lauber, 2006). Furthermore, only support in pre-market phases was allowed for the Ministry of Research. Nuclear R&D received much more funding, and there was little willingness to support the transition from research to market (Jacobsson & Lauber, 2006).

Table 6.1: Total German R&D spending on PV in million USD (2010 prices and exchange rates) (IEA database, 2011)

1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
1,499	14,208	23,275	5,285	8,114	112,795	89,921	28,584	123,954	47,592	67,368	59,195

The funding of research really picked up in this period (especially since 1982), as pressure from public opinion and political interest in PV grew, which can be seen in table 2 by comparing the 1974 with the 1982 value.. This spending declined from that year onwards until the year 1986 (the year of the Chernobyl nuclear disaster), at which point in time the declining trend was reversed. (Jacobsson & Lauber, 2006). Both research institutes and industry were granted funding for research. In the period 1975-1985, contracts were given first to silicon related research: Wacker Chemie (which focused on silicon) and AEG (which focused on the cells and the system) (Bruns et al., 2011).

Research in this period was done regarding all parts of the production chain through demonstration projects, as well as handheld appliances (Bruns et al., 2011). Also, new base materials, cost-effective production processes and the compilation of technical and meteorological data were researched. The first research institute for solar energy systems which was not related to a university (the Fraunhofer ISE) which was founded in 1981, next to the government which provided funding (Bruns et al., 2011). The Fraunhofer ISE, which is specifically focused on PV, was part of the larger Fraunhofer Institute. The institute was growing rapidly in this period, and its willingness to startup and invest in a new institute specifically for PV shows that PV had created expectations by this time to be a significant source of future energy supply. Also firms such as NUKEM (a firm related to nuclear energy) and MBB (an aerospace company) were involved in the research of crystalline silicon cells at the end of the 70'ies, following AEG, Siemens and Wacker Chemie (Bruns et al., 2011).

It must also be mentioned that the production of solar cells builds on a number of industrial branches, for example chemistry (for wafer manufacturing), semiconductor technology, glass technology, plastics technology and microprocessor technology (Bruns et al., 2011). This mean that a lot of the knowledge was already developed at the time, but still a lot of development was needed in order to transfer the technology from the laboratory to industrial production processes (Bruns et al., 2011).

Thin film

Later in this period also thin-film research started to get funding, for example at Siemens which researched thin-film and source materials. Although the focus of the research funding in this period was c-Si cells and modules, funding was also granted for research on a number of thin-film technologies, such as a-Si, copper sulphide, cadmium selenide, cadmium telluride and CIS cells (Jacobsson & Lauber, 2006). In this period in 1976 the first papers based on a-Si:H devices were published (Müller, 1986).

Furthermore, in 1979 NUKEM (a subsidiary of RWE) started research on thin-film production at industry scale, based on the copper sulfide technology (CdS), and *a-Si*

In 1980'ies a research project was launched by MBB which revolved around production of thin film silicon solar cells (a-Si). This was also researched by Siemens and AEG (Bruns et al., 2011). In 1981 MBB filed for a patent for a a-Si solar cell (Google Patents, 1981). Another example of industrial research on a-Si cells in this period can be found in Siemens, which besides working on c-Si PV also worked on a-Si solar cells. Also, the main goal of PV research in this period is identified to be the application of PV in terrestrial applications (Krühler et al., 1986). Another industrial example of research on a-Si can be found in AEG Telefunken, due to a paper that appeared in 1984 on the use of antireflection coatings used on solar cells, more specifically a-Si thin film solar cells are used in the experiment (Niemann E., 1984). Also MBB was active in the area of a-Si research as mentioned earlier. This is also indicated by a paper that appeared in 1984 on preparation methods of a-Si solar cells, which also discusses results of cells prepared in a glow discharge (Winterling, 1984). An example of university research on a-Si comes from the faculty of physics within the University of Kaiserslautern (Müller, 1986). Also the university of Stuttgart was active in the field of a-Si research, as is evident from a paper that appeared in 1985 on doping for a-Si:H thin film solar cells (Bauer et al., 1985). The research was effective in that the efficiency of a-Si cells was increasing as can be seen in figure 6.2.

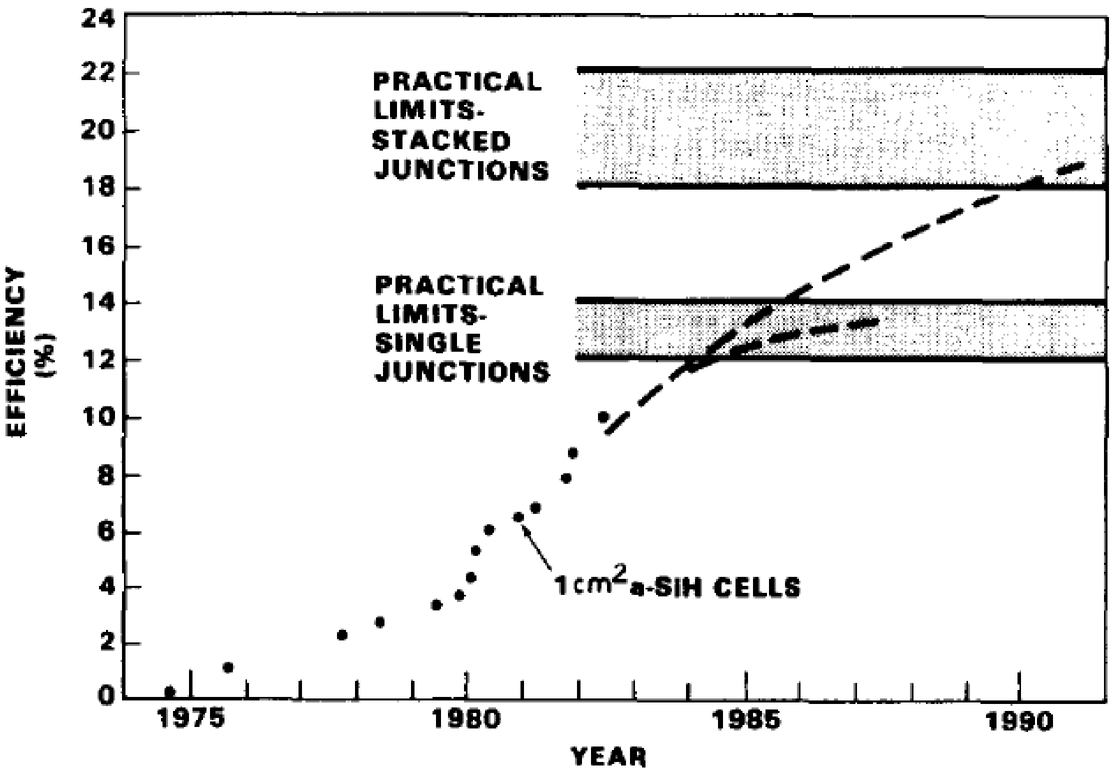


Figure 6.2: Development of efficiencies of a-Si cells (Carlson, 1984)

CIS

With regard to CIS developments, these took place in parallel in laboratories worldwide and it is therefore difficult to say who can claim novelty in development in the world or industry (Wirtz & Janssen, 2010). However, within Europe one type of process originated at the University of Stuttgart (1975) in the form of fundamental research into new materials and process development. At this university in the Institute for Physical Electronics (IPE), a CdS cell was developed before that and already in a pilot production line in the 1970’s (ZSW, 2011). The process for CIS was later exploited by Würth Solar. (Powalla et al., 2005). Würth Solar was furthermore the first company in the world to mass-produce CIS solar cells (Wirtz & Janssen, 2010), starting in 2006. The research on CIS solar cells furthermore went on in this period as is evident from a conference paper originating from the University of Stuttgart which describes the preparation of a particular type of CIS thin film solar cell (Arndt, 1985).

Supporting technologies

In this phase research funding was also allocated for a variety of topics relating to the application of PV technology, such as inverters.

6.2.2 Learning by doing

In the early phase of PV technology, i.e. when the price was still very high and the demand production volume low, economies of scale did not exist and there were no significant cost reductions (Bruns et al., 2011). Even later on, when the first PV power plant (installed in 1983) was showing the potential of PV, rapid increases in efficiency were not yet achieved (Bruns et al., 2011).

6.2.3 Learning by using

In this early period learning by using did only take place on a very limited scale (due to the limited application). In 1983 for the first time in Germany a multi crystalline solar cells demonstration project took place (300 kWp), which was financed by the federal government. This project had to shut down in 1989 due to electrical insulation defects (Schlenker et al., 2006). Measurements of this project have been conducted, however this seem to have taken place only after this period(Ambrosone et al., 1991).

In 1985 demonstration project was initiated that revolved around the application of solar cells in decentralized applications (e.g. street lamps), which led to the further expansion of the scope of PV technology. The program eventually resulted in new knowledge on the application of PV technology (Bruns et al., 2011).

6.3 Knowledge diffusion

In this period the German Society for Solar Energy (DGS) was founded (1975). “*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.*” (Jacobsson et al., 2004). In 1978, the German Solar Energy Industries Association was founded. The organization initially busied itself with spreading technical information on solar energy. However, in the 80’ies it started to work on influencing members of the German parliament

(Jacobsson, 2004). Furthermore, the German Professional Association of Solar Energy was founded in 1979. Besides promoting solar energy through institutional change, such organizations also contributed to formatting and spreading standards across the industry (Jacobsson et al., 2004).

Important in this period with regards to knowledge diffusion was the cooperation of industry with research institutes. For example, Siemens AG in this period was cooperating with the University of Hannover (Fenzl et al., 1984).

Thin film

An example of cooperation on a-Si thin film research can be found in MBB and the Max-Planck-Institut für Kernphysik in Heidelberg, as a paper appeared on glow discharge deposited a-Si thin films which involved two researchers from both organisations (Müller et al., 1983).

Also, with regards to CdS cells thin film cooperation, industry-research cooperation can be found. NUKEM in this period had taken over the production technology which was developed at the IPE at the University of Stuttgart, which represented the most advanced stage of production on CdS at the time in Germany (Pfisterer & Bloss, 1984). Thus an important aspect of the cooperation was the transfer of the research from the laboratory (originating from the university) to an industrially exploitable production process (conducted by NUKEM).

6.4 Guidance of search

Due to the energy crises in the 70'ies, the energy household had to be reviewed and this led many to see renewables as the option to be pursued by the government.

Study from the Commission of the European Communities on PV

From a European level, the Commission of the European Communities started a comprehensive assessment study for PV related to Europe. In the study, experts from nearly every member state of the European Community were involved. In the study, the US is mentioned more than once in a best practice fashion (Starr, 1983). This is probably due to the fact that most of the investments into PV were in the United States from the mid 70'ies during this period. Large investments in manufacturing facilities were done (particularly by oil companies), and the public R&D funding in the US increased from $1 m in 1974 to over $100 m in the late 90'ies. In the early eighties cutbacks were made, but still the public R&D spending was over $30 m annually (Starr, 1983). Furthermore, from the early 70'ies onward in the US goals for price were established and cost reductions were evaluated. The assessment studies concluded that already in the early 90'ies PV would become competitive, which was based on cost projections for modules and systems as shown in figure 6.3. The reason for mentioning this here, although these studies were not from German origin, is that it is likely that these studies, along with their goals, evaluations and visions, inspired the European study conducted in 1981 as prior to that no comprehensive European assessment had been conducted. In fact, the summary of the findings of the European study by Starr (1983) reveals that in order to discuss prospects for PV in Europe, it was considered necessary to look at price trends for systems and modules which were based on the goals of the US Department of Energy as shown in figure 6.3. This was, as mentioned, due to the fact to no such studies for Europe had been conducted. With at that time recent information from manufacturers and parties close to industry in Europe, the US and

Japan, the cost projection made in the US was updated and was referred to as the “1982 CEC photovoltaic cost projection” (Starr, 1983). The projection is shown in figure 6.4.

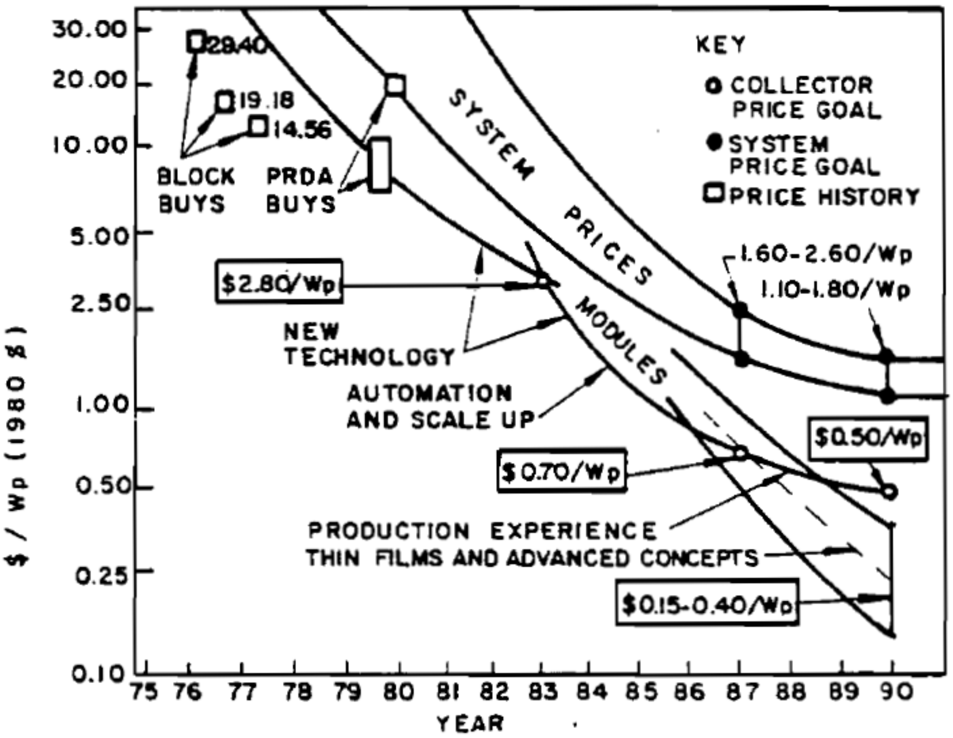


Figure 6.3: US Department of Energy draft goals for costs of PV modules and systems (1980$) (Starr, 1983).

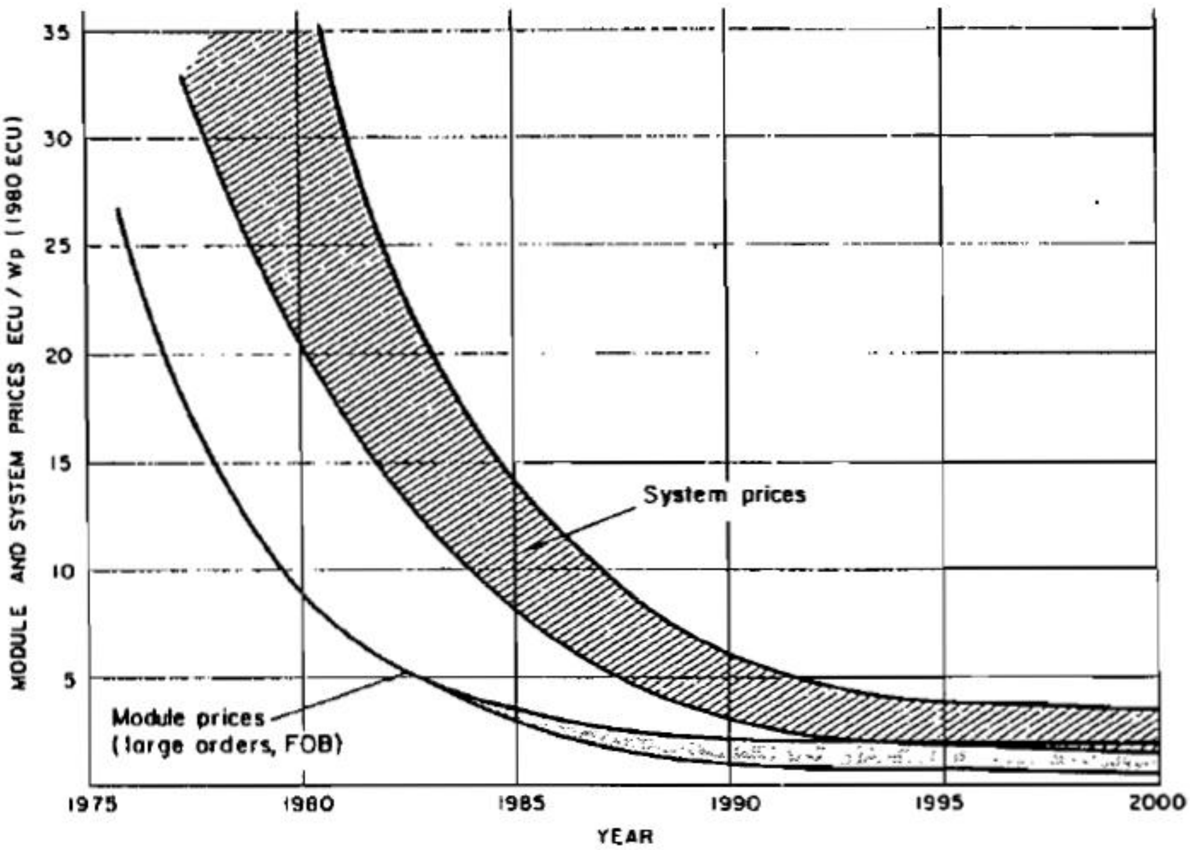


Figure 6.4: CEC 1982 cost projection for sustems and modules in 1980 ECU (Starr, 1983).

According t Starr (1983), demonstration of the technology, the need for “official encouragement” and appropriate tax and other incentives were in this time already identified as necessary in the report. Furthermore, it was stated in the report that the expectations of PV becoming competitive with grid suppliers in countries with less solar irradiation (of which Germany is one) pointed to a period between 2000-2005 (Starr, 1983). On hindsight this was an optimistic estimate but it did contribute to creating expectations as it suggested that PV would be competitive with grid (and thus large scale) supply, thus giving prospects of a large scale market.

The report not only states goals and expectations with regard to the modules and systems themselves (e.g. efficiency and cost), but also with regards to the marketsize. For example, the report mentions small stand-alone systems (up to 500W) as a market in which PV will reach competitiveness earlier than the grid- connected market, and that it will reach a size of at least 12 MWp in 1995 and grow over the next 10-15 years (from the early eighties) with a stabilization at 150 000 systems annually. However as will be pointed out, the majority of systems would later on be grid-connected. This also seems to be an expectation in the report, as the summary expects a growth of 800MWp/year in 2000 for grid-connected systems, which is a lot higher than the expected growth for stand-alone systems around 2000: 150 000 systems of maximum 500W means 150 000 * 0,5kW = 75 000 kW annually, which in turn equals 75MW annually. Thus the growth for grid-connected systems in terms of MW was expected to be more than 10 times the growth of small scale stand-alone systems around 2000. In fact, the expectation for 2025 was even 2000MWp/year. Also the market for industrial systems (i.e. in size much larger than residential systems, but smaller than utility scale systems) was estimated to reach 1000 MWp by 2000 and sales of 500MWp/year. With regard to central utility scale generating stations, this market was expected to reach an installed capacity in the order of 50GW by 2025. (Starr, 1983). It was however also acknowledged that these estimates were speculative and depended on many factors, particularly on the cost of future systems, and that suitable support for the PV sector was essential in order for the goals to be reached (Starr, 1983). An overview of the market projection is given in figure 6.5.

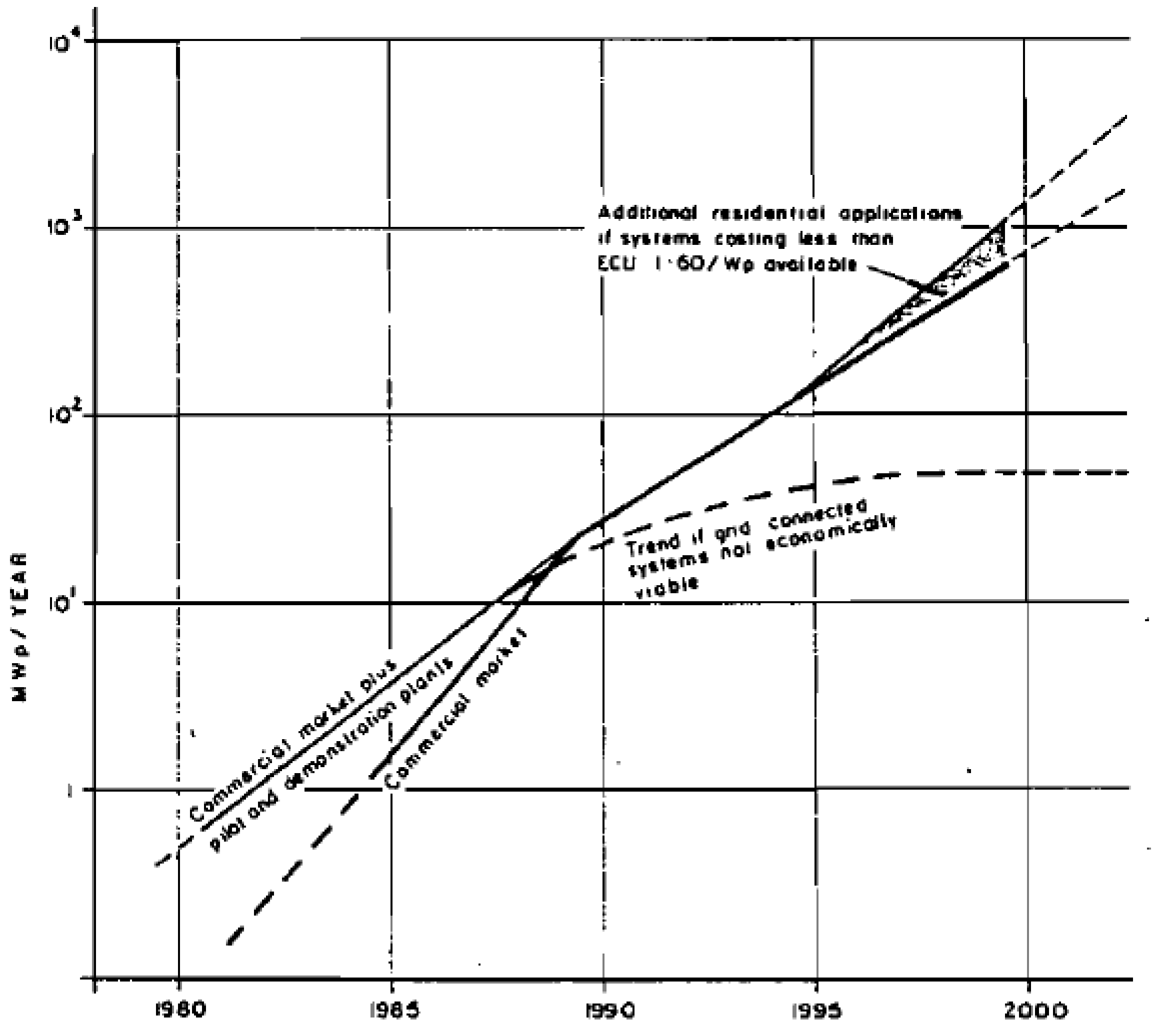


Figure 6.5: Market projection based on the CEC 1982 for PV systems in Europe (Starr, 1983)

Furthermore, the Commission of European Communities sponsored PV pilot plants within Europe, in order to increase industrial experience needed to secure order for export and in order to prepare for PV markets in the future in Europe (Starr, 1983). Apparently the foreign markets played a role in increasing the expectations for PV manufacturing in Europe, which is not surprising as at that time the US en Japan were also involved in energy research and PV and presented large potential markets.

The Commission of European Communities also funded research: about $16 million from 1979 to 1983 for more than 50 PV R&D projects was granted. Furthermore in the report a sort of enhanced follow-up budget is suggested, with a similar range of topics but more focused on now perceived priorities.

Also expectations are stated for such topics to be featured which have been shown in table 6.2 which was based on the summary of the CEC report by Starr (1983):

Table 6.2: Future expected topics in 1983 in the next CEC program

Cells	***Components & Subsystems***	***Systems***	***Production equipment***
Solar grade silicon	Energy storage systems of various types	Pilot plant construction for different applications (Residential grid connected, large central utility scale systems etc.)	Test equipment that is needed for a growing PV industry and support development of main production items from European sources
a-Si thin film cells	Array structures	Studying implications of decentralized grid connected power generation integrated with large grid networks	
CdS thin film cells	Power conditioning equipment		
Ribbon Silicon techniques			
Silicon wafer cutting			

Furthermore, the Commission of European Communities started in the development of standards for PV performance measurements and module construction (Starr, 1983).

From the report it can be concluded that expectations were high and that it was expected that PV over time would provide a significant share of the energy. Falling prices of PV systems, triggered by incentives and support, would lead to a larger market, improved techniques and more production, thus leading to further decrease in prices, making more and more types of PV applications economic (Starr, 1983). Reflecting on the table, it can be seen from the earlier section on knowledge development in this period that Solar grade silicon was an important topic in research at the time. This fact and the fact that it is mentioned under future research topics in the CEC report shows that there was a common vision with regard to at least part of the research spectrum. This could indicate a successful functioning of the *Guidance of search* function, but this is not necessarily so. It could be for example that the need for further research on some topics is so obvious that it does not need any guidance of search.

Within Germany

Within Germany an Enquete commission of German parliament in 1980 advised that renewables should be one of the first priorities of the government, although alongside nuclear energy (Jacobsson & Lauber, 2006). Furthermore, a study was commissioned in 1981 by the Federal Ministry of Research and Technology which basically stated that reliance on renewables and efficiency was the only real way forward (Jacobsson & Lauber, 2006). With regard to the federal R&D programs, besides creating new knowledge they also fulfilled the function of guiding the search into solar cells (Jacobsson et al., 2004).

Also around 1980, an expert committee on energy technology on behalf of the government came with recommendations on the expansion of innovative research topics at the Ulm university (a smaller university founded in 1967 in the state of Baden-Württemberg, which frequently finds itself in top domestic rankings in natural sciences). The most promising areas that were identified by the committee were electrochemical energy conversion and storage, along with the corresponding processing technologies (Photovoltaic cells are a subgroup of photoelectrochemical cells, which in turn falls under electrochemical energy conversion(Parkinson, 1983). Thus, the committee recommended to intensify these topics within the Ulm university curriculum and also to establish a non-university research institute that would work closely together with industry (ZSW, 2011).

In the early phases (i.e. until 1985) of PV technology, industrial actors harbored very high expectations of the technology. They were however mistaken that the industrialization of PV technology was already close at hand (Bruns et al., 2011).

An overview of public funding for research, development and demonstration for PV in Germany in this period is given in figure 6.6.

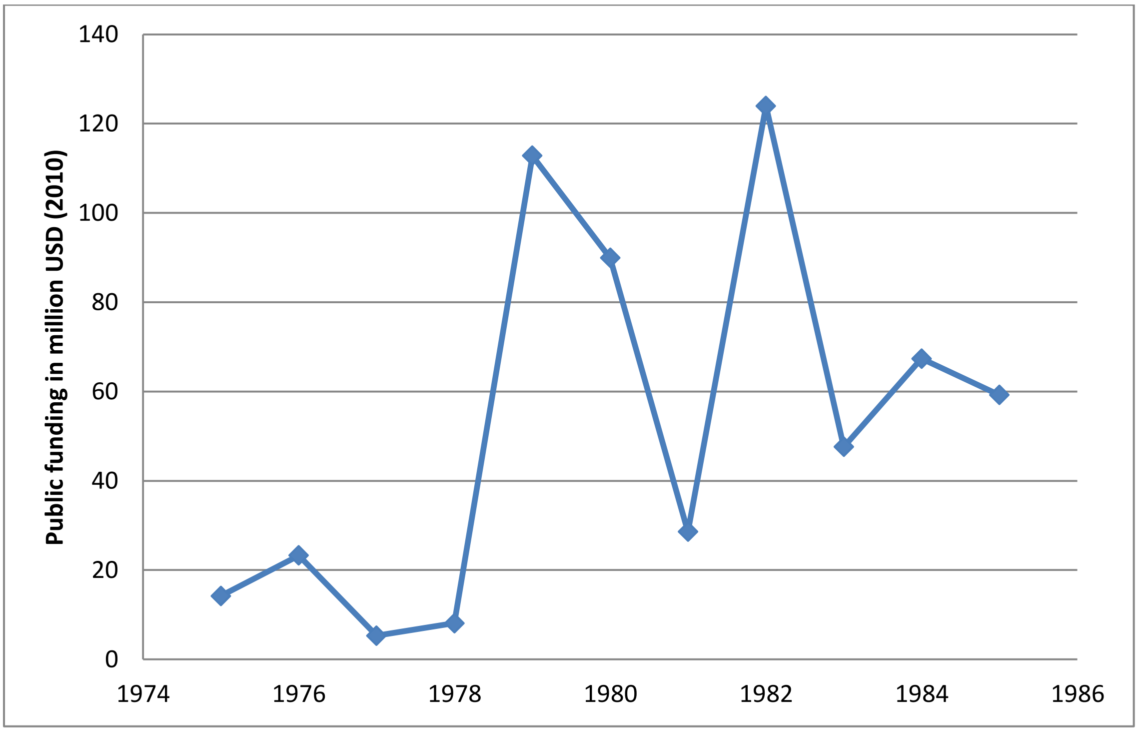


Figure 6.6: Total RD&D on PV in Germany in Million USD (2010 prices and exch. Rates) (IEA Database, 2012).

It can be seen that although public funding for PV with regards to RD&D was fluctuating in this period, a rising increasing trend can be discerned. This indicates that over this period an increasing importance was attached to PV both from a European as well as German federal level, and that positive expectations were harbored with regard to its potential.

However, there is also data that indicates a steady increase in government support from BMFT, the Federal Ministry of Research and Technology (as well as industry expenditure) for R&D on PV as can be seen in figure 6.7. The two graphs that are apparently contradicting can possibly be reconciled by noting that figure 6.6 gives not only R&D budgets, but also budgets for demonstration, and that figure 6.6 represents the total government funding whereas figure 6.7 represents only the part from the BMFT. Figure two clearly shows an increase in both industry and BMFT support, indicating that the expectations for PV were rising in this period (Pfisterer & Bloss, 1989).

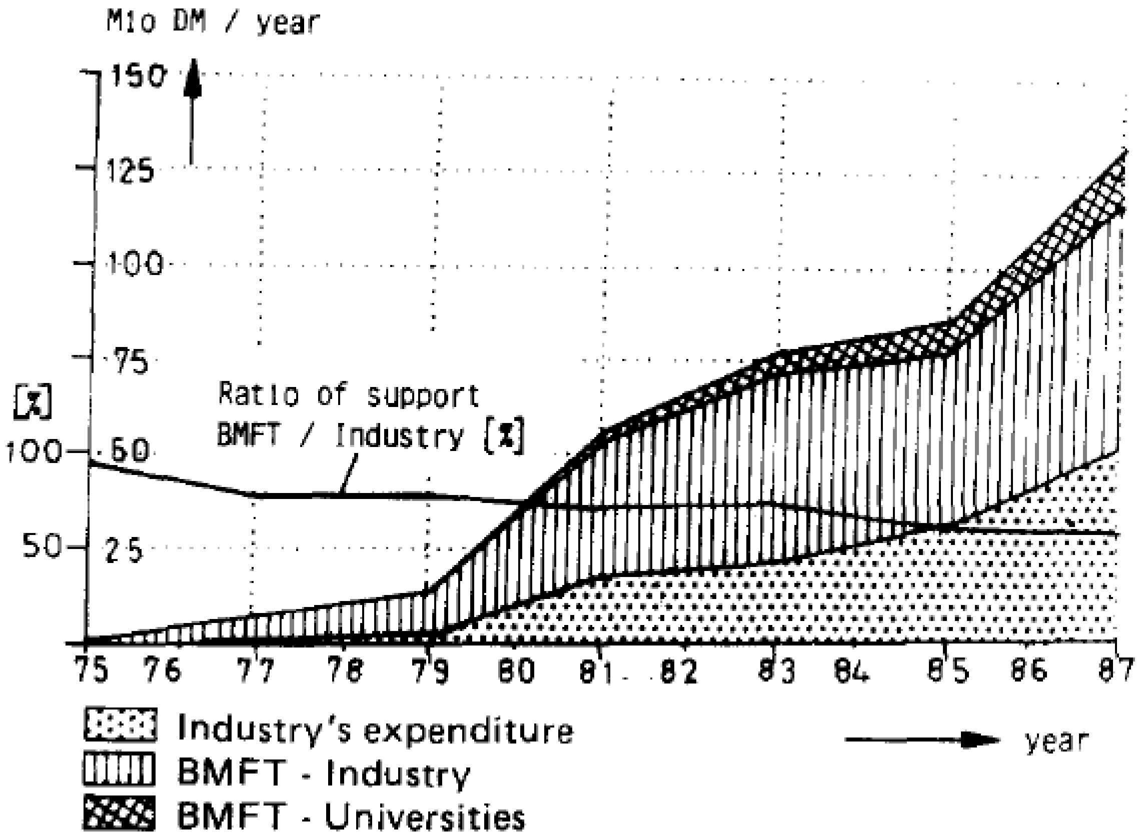


Figure 6.7: BMFT (Federal Ministry for Research and Technology) support and industry expenditure for PV R&D with DM in millions between 1975 and 1987 (Pfisterer & Bloss, 1989).

The support from BMFT for development was primarily for technologies that had already proven to work, in order to make their use more economical (Pfisterer & Bloss, 1989). This can be seen in figure 6.8.

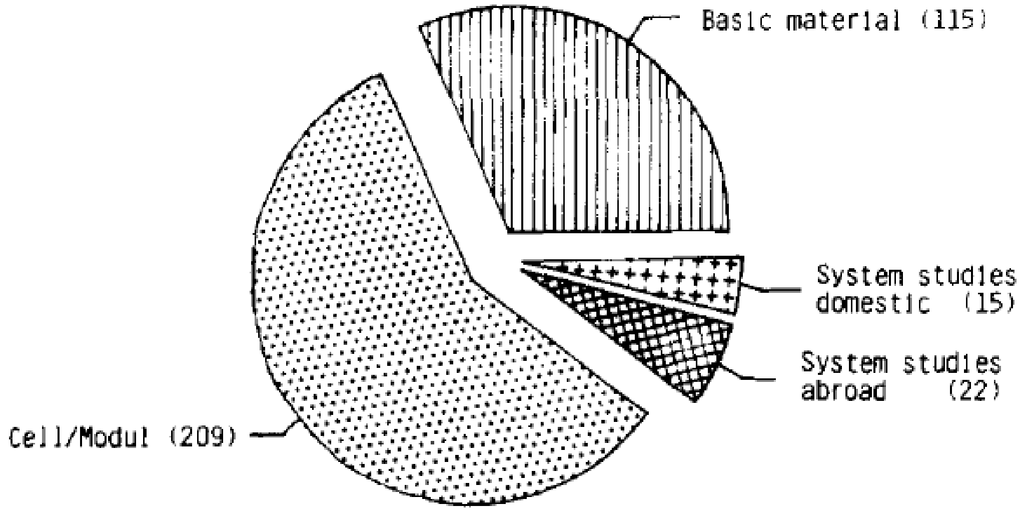


Figure 6.8: Support from BMFT for PV R&D from 1975 until 1986 (Pfisterer & Bloss, 1989).

The fact mentioned earlier that the BMFT funding focused primarily on proven technologies (indicating that new thin-film concepts were considered less relevant) seems to indicate that the BMFT wanted to establish these proven technologies such as c-Si modules first, and thus capitalize on the expectations of larger scale power generation by PV.

Thin film

The thin-film technology considered as having the most potential was a-Si PV technology, and this technology received most of the funding granted to thin-film technologies (Jacobsson & Lauber, 2006). This PV technology was identified to have a number of advantages over c-Si solar cells, including the higher absorption coefficient leading to lower material use and more possibilities for deposition on different kinds of substrates at higher temperatures. A disadvantage however was and is the lower efficiency. As pointed out earlier, thin film technologies had R&D funding from the government.

6.5 Market formation

Whereas before 1970 the demand for PV from the space sector exceeded the demand for domestic applications, in 1970 for the first time demand for domestic applications of PV exceeded demand from the space sector.(Bruns et al., 2011). It is difficult to give a specific reason for this increase in demand from the domestic sector in this period, partly due to the lack of data available from this early period. Perhaps it could be a matter of "technology push". Nonetheless, the amount of companies active in Germany on PV was still small.

Although during the oil crisis incentives were created for utilities to use hard coal in 1974-1975, little was done at this time by the Ministry of Economic affairs (which was normally responsible for market formation programs) to create a market for renewable energies. A general competition law was adopted, which obliged utilities to buy electricity generated from renewable sources in their supply area at the price of avoided costs, but this law was interpreted in a very narrow way by utilities (i.e. only avoided fuel costs). As a result, the law did not have much effect. In effect, the ministry did not cooperate in market formation under the banner of not subsidizing technologies that were not mature (Jacobbson & Lauber, 2006). The cost of producing solar cells in this phase was still very high and efficiencies were low, as a result of which solar cells were only attractive in particular niches or applications that were isolated such as a wrist watch (Bruns et al., 2011).

6.6 Resources mobilization

Capital

At this point in time it seems that entrepreneurial activities were still risky from an economic perspective, as there was only a small market and prospective growth was only just emerging. This is confirmed by the type of firms active at this time in the PV sector. None of them (e.g. AEG, NUKEM, Siemens, MBB) was specialized in PV, but rather had PV as a small part of their business. Such companies were subsequently able to take the risk of engaging in this developing market; they had their own capital and were not in need of venture capital.

Worth to mention here is that the West German government did provide assistance and support to the German semiconductor industry (97.4 D. in 1978) (Morris, 1990). This is relevant due to the fact that the semiconductor industry is related to the PV industry, and support for the semiconductor industry could be seen as an indirect and partial support of the PV industry.

Employees

With regard to research employees, it appears that these were available through the related industries which were established already in Germany. For example, Siemens and AEG Telefunken, which were both vertically integrated companies and a broad interest in the field of electronics, dominated the electricity industry in this period (Morris, 1990). Thus these firms could build on their existing knowledge base and move into the related field of PV and it is no coincidence that they both became active in the field of PV, as they had relevant expertise.

Specialized education programs

This period was characterized by a small niche market which only existing firms could afford to engage in as part of their business. Since the PV market was still at an infancy stage, no education programs existed with a focus on PV. PV after all was not a completely new stand-alone technology, but rather strongly related to existing technologies, for example semiconductor technology and chemistry/metallurgy. Thus in this early period the existing knowledge complemented by research was sufficient to start development of PV applications.

Availability of raw materials

At this point in time the market was of such a small size that raw materials were sufficiently available.

6.7 Advocacy coalitions

In this period a variety of actors entered the scene, actors which would later become key players in advocating solar power. For example, 1979 witnessed the foundation of the Association of Solar

Energy SMEs, which became German Solar Energy Industries Association in 1986 (Bruns et al., 2011). This association was mainly occupied with lobbying campaigns for the PV industry (Bruns et al., 2011). Also in this period the German Society for Solar Energy (DGS) was founded in 1975. *"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."* (Jacobsson et al, 2004). Such associations represent the most important force in lobbying (Bruns et al., 2011). They also helped shape a positive image of solar energy through information campaigns, conducted over several years. Also, due to the controversy surrounding nuclear power, environmental organizations developed themselves and were able to provide independent expertise. An example of this is the Institute of Ecology, which was founded in 1977. This institute became instrumental in the development of proposals for renewable energy policies (Jacobsson & Lauber, 2006). et al. 2011).

6.8 Conclusion

In this early period there were few firms active in the PV sector. Reflecting on the involved firms, it can be seen that both AEG and Siemens were large firms active in the electronics industry, engaging in PV for a (small) part of their business. There were no specialized firms focusing only on PV as was the case in later times. This could mean a number or combination of things, including that the market was small, the risks at this stage were such that only large companies could afford to dedicate part of their business to PV, and that there was no prospective growth yet. Also research on PV was starting to develop, as was indicated by the growing number of papers from German origin. Furthermore there was a broad scope of the research with regard to the different PV technologies. Also, cooperation took place between industry and research institutes on both crystalline silicon and thin film technologies, showing that important infrastructural conditions were in place for knowledge transfer between the lab and industry. It is likely that these developments partly were fueled by developments abroad, such as in the US as was shown in the guidance of search function. Investments there were much higher than in Germany, and the developments there gave rise to expectations for grid parity and so on. Although these expectations were optimistic on hindsight, they did create positive prospects for PV. PV at this time was still more of an R&D topic, and not ready for widespread diffusion on the market, and no such measures were taken by the government. There were no specialized firms in the field of PV yet, and mainly large cooperations were able to invest a part of their resources into PV development. Furthermore, in this period some advocacy coalitions came into existence, which shows a growing drive from the public sphere. Key roles were later on to be played by these coalitions, thus in this period an important basis was laid down for large scale diffusion later on.

7. 1986-1991

7.1 Entrepreneurial activities

In the wake of contextual events (e.g. the nuclear disaster in Chernobyl) there were a lot of expectations for solar energy in the industry. However the developments of efficiencies of solar cells did not live up to that expectation. This led to a decreased interest from industry in solar cells (Bruns et al., 2011).

Silicon

As a result, in this period and beyond a number of mergers and takeovers took place, due to a change in strategic orientation that was deemed necessary due to the *increasing efficiencies that were achieved in countries abroad*, but for which Germany was not prepared (Bruns et al, 2011). For example, NUKEM and the aerospace company MBB moved into a joint venture for the development of CdS (Cadmium sulfide) thin film cells which failed to materialize, and NUKEM subsequently moved its focus to crystalline silicon technologies (Iken, 2005).

In the second half of the 80'ies, the first grid connected PV systems were installed, mostly on private residential buildings (Bruns et al.,2011). Further information on this however could not be found.

In 1989, Bayernwerk AG (a large electricity supplier in the region of Bavaria) acquired a 49% share in Siemens Solar. In 1990, Bayernwerk AG had contracted the construction of its first solar power plant (368 kW of capacity) in Germany. The construction of the power plant was within the Solar-Hydrogen-Bavaria project (BAYSOLAR). This project, along with the HYSOLAR project (which only involved research institutes and universities at this time and is further explained under the second function), served to *"demonstrate the complete supply chain of a solar hydrogen energy economy"* (IPHE, 2011). The projects, that were both concluded in the 90'ies, had shown that the main parts of a hydrogen energy system were developed and could also function, however feasibility of a solar hydrogen economy could only be reached in the distant future (IPHE, 2011). The project solar power plant project was conducted in cooperation with Siemens, MBB, Linde and BMW. A significant outcome of this joint venture was, besides learning on the solar hydrogen energy systems, the foundation of Siemens Solar by Bayernwerk and Siemens. In 1989, two AEG divisions merged with MTU (a German aircraft engine manufacturer) and Dornier (a German aircraft manufacturer), which were all aerospace interests of Daimler-Benz. Later in the same year Daimler-Benz acquired MBB to form DASA (Daimler-Benz Aerospace).

Thin film

In the 80'ies it was thought that a-Si thin film solar cells would be the thin-film technology to eventually replace c-Si solar cells. With this in mind, by the end of the 80'ies MBB built a pant solely dedicated to a-Si solar cells production (Jacobsson et al., 2004). MBB was the basis of the spin-off company Phototronics Solartechnik (PST) which was founded in 1988 (Bruns et al., 2011). MBB was taken over by DASA (Deutsche Aerospace AG), renamed "Daimler-Benz Aerospace" in 1995. Later on the knowledge of these companies would be integrated into SCHOTT Solar (Schott Solar, 2006). In 1987, Siemens also -enters the thin-film arena through a-Si cells in cooperation with Arco. In 1988 their joint venture PV Electric GmbH is founded. In 1989 a pilot line is started for a-Si cells with an annual capacity of 1MW. Furthermore in 1989 the planning by Siemens en Arco takes place of a

20MW plant in West Germany that will produce a-Si solar cells. The plant was formerly used for reprocessing nuclear fuel, but after the government abandoned it in 1989 Siemens, ARCO and Bayernwerk decided to convert the plant to a solar cell factory (New Scientist, 1989). The target was to start production in 1994 (Frank Media Info, 2011).They further planned to use automated production to reduce the price at the time of $4 with 50% (New Scientist, 1989). In 1990 Siemens takes over ARCO and becomes the world leader in a-Si solar cells (Frank Media Info, 2011). But besides a-Si technological know-how, through ARCO Siemens also acquires knowledge on CIS cells due to the fact that ARCO had been an early mover in this field (McEvoy et al., 2011).

Even though there were entrepreneurial activities, there was no relatively significant outdoor market for higher wattage applications yet for a-Si thin film solar cells, or thin film cells in general. The reason for this seems to be the low efficiencies at the time of a-Si cells (about 4-5%), which implies that the total system costs are comparatively high in applications where costs of mounting, wiring, area etc. are high. A higher efficiency means that less area has to be covered and thus the system costs go down (Carlson, 1991). Thus a-Si cells, which dominated the thin film market, were primarily used in applications such as calculators. In fact, a-Si cells in this period even accounted for 40% of all PV sales (Carlson, 1991). This is a radically different figure from today where the overwhelming majority of sales is for crystalline silicon cells. At the same time this indicates the small size of the market at this time.

7.2 Knowledge development

7.2.1 Learning by searching (R&D)

Silicon

In this period, research was carried out by universities, industry and solar energy centers that were newly established (as will be mentioned shortly). An overview is given in table 7.1.

Table 7.1: Overview of parties doing silicon related research based on Pfisterer & Bloss (1989).

	Industrial R&D	University & Institution R&D
Silicon	- ***Basic material***: o Wacker o Siemens o Bayer - ***Wafer manufacturing***: o Wacker, o Siemens - ***Solar cell processing***: o AEG o Siemens o Telefunken o Wacker	- ***Wafers manufacturing***: o RWTH, o ISE Freiburg - ***Fundamental R&D on cell***: o University of Konstanz, o Max-Planck Institute o TU Berlin - ***Calibration & Diagnostics***: o PTB

A search through Scopus revealed that little research on c-Si solar cells was published in this period. The research that was conducted seemed to be on new ways of silicon growth, for example Siemens

AG, of which the majority of its publications were on a-Si this period, only had about two articles on c-Si, more specifically on the supported web technique for Si growth, e.g. Grabmaier & Falckenberg (1990)

In this period the Second Energy Research Program was still running (1980-1989). This program expanded on promoting technologies for the harnessing of solar energy, and with regard to PV its' focus was on conducting basic research, minimizing the costs of thin-film solar cell production, conducting research into new materials, cutting the costs of production procedures and silicon manufacture and at the same time higher efficiencies (Bruns et al.,2011). As efficiencies of the cells were low and the cell was thick (and thus the material use was high), a prime focus of this program was to come up with thinner wafers and higher efficiencies, next to reducing losses in production (Bruns et al. 2011). Although general information on this early energy research program could be found, more detailed information seemed not to be available easily. Funding of research into renewables rose significantly during this period, following the Chernobyl disaster in 1986, and thus also the funding for PV research, as can be seen in figure **7.1**.

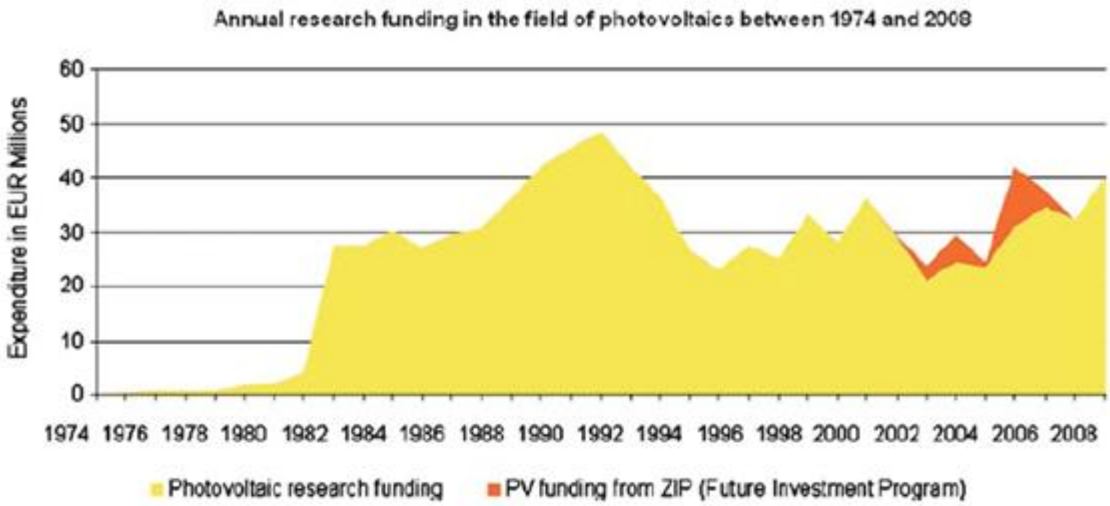


Figure 7.1: Federal grants for PV projects (Bruns et al., 2011).

In this period a number of research institutes were founded. In 1987, the Institute for Solar Energy Research Hameln (ISFH) was founded and in 1988 the ZSW in Stuttgart and the ISET in Kassel were founded. The institutes furthermore worked closely with industry (Bruns et al.,2011). In this phase, the niche of photovoltaics was protected by federal and state funding, while the industry engagement declined. Research on PV, which investigated knowledge on the application of PV, increased after the Chernobyl accident and a number of PV applications were further developed (Bruns et al., 2011).

Thin film

Especially thin film research was funded in this period, which was for 70% subsidized (Bruns et al., 2011). In 1989, the University of Stuttgart achieved efficiencies of 15-17% with CIS solar cells (Wirtz & Janssen, 2010). An overview is given in table 7.2.

Table 7.2: Overview of different parties engaged in thin film R&D partly based on Pfisterer & Bloss (1989).

Thin film	- **GaAs:** o Telefunken - **a-Si:** o AEG o Siemens, o MBB/Phototronics - **CdS:** o NUKEM	- **GaAs:** o ISE Freiburg, o University of Stuttgart, o Max Planck Institute o Batelle Institute - **a-Si:** o University of Marburg o IPE o University of Stuttgart o Max Plank Institute o KFA Juelich o University of Kaiserslautern o University of Frankfurt o HMI Berlin o University of Konstanz o ZSW - **CIS:** o IPE o University of Stuttgart o Batelle Institute o HMI o Siemens

With regard to a-Si, an example of university research can be found in the University of Mannheim which was conducting research on a-Si cells. An article that appeared from this University this period has the nature of basic research, but was clearly aimed at eventual application (Block et al., 1991). It describes a computer simulation model of amorphous silicon thin-film solar cells, aimed at the modeling of an added layer (SiGe) to the cell for countering the Staebler-Wronski-Effect. This effect, according to the authors, is the reason that large scale terrestrial application was still elusive at this point (Block et al., 1991). The Staebler-Wronski-Effect leads to a reduction of energy conversion effiency of the cell, making it less suitable for this large scale terrestrial application. As the authors mention it in their paper to justify the relevance of their research, this furthermore points out that large scale terrestrial application at this point in time was already driving at least some university research.

With regard to a-Si research in industry, Siemens AG seems to be the most active as indicated by over 20 papers in this period on a-Si were found from Siemens by comprehensively searching "solar cells" in the Scopus database. In fact it seems that Siemens was more active in a-Si research than it was in the area of silicon PV, as about 11 papers on a-Si appeared.

Furthermore, a search through Scopus ("solar cells") showed 189 German publications, of which the most popular topic was a-Si. For example, the journal containing relatively most of the found publications in this period on solar cells was the *Journal of Non-Crystalline Solids,* of which by far most of the found 21 publications were on a-Si.

GaAs

Interestingly, a search on Scopus ("solar cells") described previously showed that the European Space Agency Special Publication contained the most articles after the *Journal of Non-Crystalline Solids* with 17 articles, of which about three were on GaAs.

CIS

The Hahn Meitner Institute (HMI, and today the Helmholtz center Berlin) seemed to have been an important player in this field at the time as is indicated by 8 articles on CIS that appeared on the topic. Not much later Sulfurcell, a CIS startup, would emerge as a spin-off from the HMI. The research on CIS at this point still seemed to be rather basic instead of applied.

There is also evidence that Siemens was active in the field of CIS research. This is due to the fact that it was cooperating with ARCO, an American oil company, in this period on thin film cells. Arco already had knowhow on CIS, and Siemens joined in in 1987 and took over Arco in 1989 (McEvoy et al., 2011). Nonetheless no papers from Siemens appear on CIS in this period; only in the next period did papers on CIS solar cells start to appear. This could imply a secrecy policy, or that it took some time before Siemens got new results. It is furthermore worth to mention that with the taking over of Arco, Siemens moved its research in part to the USA. For example a paper on the status of CIS development at Siemens Solar Industries USA appeared in 1997 (Gay, 1997).

Organic solar cells

In this period research on organic solar cells was conducted by the Institute for Solar Research in Hannover (Siebentritt et al., 1991). A research article from 1991 describes the investigation of individual components and cells forming junctions in order to determine the fundamental limitations of organic solar cell efficiencies. One reason for poor energy conversion efficiency was the low short circuit current, for which some reasons were subsequently found, as well as a possible solution (Siebentritt et al., 1991). This shows that the research at this time was still of a basic nature on organic solar cells. An interesting comparison in this regard is the fact that the theoretical efficiency limit for c-Si solar cells seems to have been calculated around 1961, for example refer to Shockley & Queisser (1961), although later reexamination and new models were used for update. For a-Si a upper efficiency limit seems to have been estimated around 1977, for example refer to the work of Carlson (1977). For CIS, likely this estimate was done around 1980, for example by Spitzer et al. (1980).

7.2.2 Learning by using

Silicon

By now, the first PV power plant that was built in 1983 showed the potential of generating electricity through solar cells (Bruns et al., 2011). Also operational experience was gained (through evaluation by CEC mentioned earlier), highlighting both strong points and aspects which needed improvement. For example, it was found that the PV modules exhibited good reliability, that galvanized steel or wood was suitable for supporting the structure but that stainless steel should be used for connecting and fixing devices (for example screws and bolts), that power conditioning systems were the part of the system with the lowest reliability and that insufficient experience was present with regard to prevention of damage from lightning (Pfisterer & Bloss, 1989). Furthermore, measurements were conducted on the 300 kW system in this period (Ambrosone et al., 1991).

Also, in 1986 a demonstration program was initiated, which by the mid 90'ies helped building over 70 larger applications PV installations in different applications. Although this did not lead to a large protected space, it did facilitate learning regarding the application of the PV technology. Not only did the firms involved in the production of cells and modules (e.g. AEG, Siemens) learn, but also further down in the value chain learning took place (Jacobsson & Lauber, 2006). Furthermore, in this demonstration program the first plant by a utility company was built, which also evaluated between 15-20 different modules and and tested how to integrate such a plant into the landscape.

CIS

For a period of about nine years (1988-1997), Siemens Solar Industries had its modules tested by NREL (National Renewable Energy Laboratory), an American national laboratory focused exclusively on *"advancing renewable energy and energy efficiency technologies from concept to commercial application"* (NREL, 2011). This led to the identification of a number of future R&D challenges that had to be overcome for CIS cells, for example the need for a higher deposition rate and a thinner CIS layer (which both increase the throughput rate, and the latter also counters the limited availability of the element "In" in CIS) and the need for higher band gap alloys (which leads to better outdoor performance (Ullal et al., 1997).

7.3 Knowledge diffusion

In this period, the Eurosolar association was founded. This association was not only lobbying for solar power, but also active in spreading knowledge on renewable energy related topics. For example, since 1989 the magazine *Solarzeitalter* is published quarterly. This magazine "*discusses renewable energy policies and economic programmes, provides a critical review of conventional energy concepts and information about political developments in support of renewable energy. It is considered the most important political magazine for renewable energy."* (Eurosolar, 2011).

Furthermore, the non-university research institutes joined forces and founded their own organization: Solar Energy Research Association (FVS). Its goal was to represent a joined force for decentralized PV research in the face of industry and politics (Bruns et al., 2011). Although this sounds more like lobbying, it also functioned as a point of contact for business, politics and research (Bruns et al., 2011). For example, in 2004 a forum was organized where perspectives of research were discussed for renewable energies in industrialized and developing countries (Renewables, 2004).

Thin film

a-Si

With regard to amorphous silicon solar cells (a-Si), cooperation in this period took place between industry and university researchers. For example, Siemens AG cooperated with the University of Technology in München on degradation in a-Si cells which is indicated by a joint paper that appeared in 1991 (Kopetzky et al., 1991). Siemens also cooperated on a-Si research with Arco (McEvoy, 2011).

MBB in this period cooperated with the Technical University of München, as is indicated by a joint paper that appeared in 1991 on a-Si which describes rather basic research (Stitzl, 1991). The basic nature of the research conducted in the cooperation of MBB with the Technical University of München is furthermore confirmed by another paper that appeared in 1989 which also describes basic research on a-Si (Wind, 1989).

CIS

Also, Siemens in this period cooperated with the American firm Arco in CIS from 1987, which it took over in 1989 (McEvoy, 2011). After that no joint papers seem to have appeared on CIS from Siemens and another research institute on this topic.

7.4 Guidance of search

At the EU level in the period of 1986-1991 climate problems were becoming an issue and climate goals were set, which increased the speed of setting up national procedures within Germany (Bruns et al., 2011). In 1990, the first IPCC document (an assessment report) outlined goals for CO2 emission reductions and climate protection, although these goals were not binding (Bruns et al. 2011).

One practical example which shows how the functioning of the guidance of search function in Germany is the so called “Glotter Talks”. These bi-annual talks took place for the first time in 1987 and involved politicians, researchers and industry. Representatives from the government met with important persons from companies and research institutes in order to discuss the future strategic direction of research and funding. Thus, research on photovoltaics was aimed towards future circumstances (Bruns et al., 2011).

Another example can be found in the State of Baden-Württemberg (home to the Ulm university mentioned earlier), where this State guided the bringing together of research subjects of the institutes in Stuttgart and Ulm (see previous period within this function), in order to establish the ZSW, a world-wide renowned institute.

In this period the Bölkow study was conducted, which was a deep study into the potential of cost reduction in PV. Most importantly, the study concluded that within 5 years the primary cost of PV modules and the production costs of PV generated electricity could be reduced to about one fourth or one fifth of the costs at that time, under the condition that module development would be exclusively oriented towards large scale power applications and a consistent contextual development of PV plant technology (Pfisterer & Bloss, 1989).

Thin film

In this period (as well as the preceding one) there were high expectations for thin-film technology. It was thought that thin film solar cells would rapidly make PV profitable, and the costs per Watt were anticipated to be 30 cents in 1990 (Bruns et al. 2011). The technologies that had proven to work, and are still used today, were CIS, a-Si and CdTe solar cells.

7.5 Market formation

An example of the promotion of the utilization of solar energy in this period is the REN program (started in 1987), which was initiated in the state of North-Rine Westphalia with the goal of stimulating rational energy use and energy from renewable resources, including PV (Bruns et al., 2011). This program has been revised and updated until today; now its focus is on the development of the energy sector (i.e. cluster) in the region (Hartmann, 2008). Primarily solar panels and systems were funded (about 26,000 panels and 11,000 systems up to 2007). The program had a significant impact on the PV sector, although it could not provide investors with long-term security due to the annual revision of the budget. Some 260 million euro was allocated to around 51,000 projects between 1987 and 2007. This resulted in investments from the private sector of about 1,5 billion euro (Bruns et al., 2011).

Furthermore, a demonstration program, from 1985 for the application of PV in decentralized applications enlarged the scope of the PV market, and two energy suppliers (RWE and Bayern) now started to fund large scale projects (Bruns et al.,2011). Although the installed capacity in 1990 was 1.5 MW, this was rising due to the demonstration program (which led to the construction of over 70 large scale applications). Also, by the end of the 80'ies subsidies of 1 DEM/W were offered to 100 facilities by Stadtwerke Giessen and a payment (on feed-in basis) of 10 pfennigs per kWh (Bruns et al., 2011)). Stadtwerke Saarbrücken offered a higher payment of 25 pfennigs per kWh for 20 years, the highest payment in Germany at that time (Bruns et al.,2011). The VSE Group AG in this period was the first to offer 1:1 compensation using reversible electricity meters.

7.6 Resources mobilization

7.7 Advocacy coalitions

In this period, the Förderverein Solarenergie was founded (1986), which in 1989 came up with the principle of "cost covering payment" for renewable electricity generation. The importance of this, is that this concept was later used in a number of Feed-In laws at a national and local level (Jacobsson & Lauber, 2006). Also, in 1988 the Eurosolar association was founded (Eurosolar, 2011). It was founded on the basis of meeting the need to "*create a public climate that would enable it to tear down the walls in people's minds*" (Palz, 2010). This non-profit European association lobbies within the political structure, but is not affiliated to any party or interest group. Nonetheless, several members of the German parliament were in the association (Jacobsson & Lauber, 2006), but also scientists, companies, associations and citizens from different occupational sectors (Bruns et al.,2011). Its' goal is to replace nuclear and fossil energy entirely with renewable based energies, and it does so by developing political and economic concepts for the implementation of renewable energies (Bruns et al.,2011). For example, this group later on proved to be instrumental in initiating the 100,000 roofs program, a program which in turn had a major impact on the diffusion of PV in Germany. In 1989, its founding member wrote a resolution for the parliament to prioritize solar energy in research and development policy, which was subsequently passed (Palz, 2010a). Political parties became more and more interested and talks (about 200 annually) were given at assemblies, universities, environmental organizations and action groups. Also, the media attention grew and calls from environmental groups for promotion of solar energy strengthened. (Palz, 2010a). Solar energy found increasing support in the party of the founding member, which was one of the two major parties in Germany (SPD), and also publicly (Palz, 2010a). After this growth of public and political support, in 1990 several other member of the parliament from other parties (CDU/CSU, the Greens), who were already members of EUROSOLAR, teamed up and this led to the first feed-in tariff law and was adopted by parliament in 1990. Important support in this regard came from the economics minister of North Rhine-Westphalia, Reimut Jochimsen (Palz, 2010a).North Rhine-Westphalia was Germany's largest federal state and he was in that period the chairman of the conference of economics ministers and had been persuaded to support the law. However, this opened up a window for wind energy but not so much for solar power, for which the investment opportunities were not yet attractive enough despite the first feed-in law. Furthermore it was difficult to achieve things beyond this, and big electricity companies tried to frustrate any efforts for the legislation up till the last moment (Palz, 2010a).

Also in the public sphere, renewables gained attention. From the mid 70'ies onward, nuclear energy became an increasingly controversial issue with the public, and many envisioned that renewable energies and efficiency should be the main priority of government instead of nuclear power and hard coal (Jacobsson & Lauber, 2006). Also on an EU level activities took place: For example, the EU took efforts to liberalize the energy markets and in 1988 the EU Commission made clear its opposition to the existing monopolistic energy structures and exclusive rights to the energy market. This eventually resulted in the German government adapting the Federal Electricity Tariff Regulation, which now made it possible for small electricity producers to receive compensation payments. These developments were greatly in favor of renewable energies in Germany (Bruns et al. 2011). This is due to the level playing field which resulted and the countering of monopolized structures (Polo & Scarpa, 2003). Founded following the nuclear disaster was the German Association for the Promotion of Solar Power (SFV), in 1986. This association made important contributions to the diffusion of PV and the creation of PV friendly institutional structures. An example of this is the cost covering payment that they developed (Bruns et al., 2011).

Conclusion:

"These three types of organizations demonstrate that photovoltaic technology found advocates at a number of levels; they gradually branched off in different directions and formed networks. During the pioneering phase and during the phase in which industry involvement stagnated, the ground-breaking work of associations and societies provided a particularly firm basis for the development of

photovoltaics. Furthermore, the organizations helped shape measures at federal, state and local level and played a major role in conveying the potential of photovoltaics (Mautz &Byzio 2005, 31; Jacobsson et al. 2002, 20)." (Bruns et al., 2011)

7.8 Conclusions

Looking at this period, it becomes clear that the main industrial players involved in PV were still large established firms, and not many new players entered. Thus the market was still at an infancy stage. It seems that there were two commercial PV technologies at this time: c-Si and a-Si thin film cells. There was no large gap between c-Si and a-Si thin film cells in terms of diffusion, at least nowhere near the gap that exists today. Furthermore the information from this period points towards the fact that a-Si was gaining increasing attention in this period, as is evidenced by the entry of industrial players in a-Si research activities and the large amount of research institutes (from university or otherwise) that were conducting research in this field as well. This is in line with the idea in this period that a-Si would be the thin film technology to replace c-Si technology. On hindsight this was an erroneous idea as the gap between the diffusion of c-Si and a-Si cells only widened in the coming periods in the advantage of c-Si cells.

An interesting observation is that while attention of research seemed to shift towards a-Si, other mechanisms favored c-Si cells. For example, a pilot plant with c-Si cells that was installed in 1983 (mentioned earlier) was now showing the specific potential of c-Si to generate power on a larger scale. This means that expectations for c-Si were generated in a potentially huge market (i.e. hundreds of thousands of roof tops and large power plants), thus contributing to the guidance of search function. Amorphous silicon cells in this period had no such reference, which is not strange due to the significantly lower efficiency of the cells. Furthermore, a program for the construction of about 70 large scale PV applications mentioned earlier also favored c-Si cells, as only c-Si cells were suitable for such application. Thus, while research seemed to be shifting towards a-Si (as indicated partly by the amount of research papers on the subject in comparison with papers on c-Si cells), guidance of search and market formation were giving c-Si cells a head start at this time already. The reason for this appears to be that c-Si at this time already had higher efficiencies. Also seemingly more general occurrences such as the foundation of advocacy organizations would later on seem favored towards PV, due to a future focus on projects where c-Si was by far the most suitable candidate at the time.

8. 1991-1994

8.1 Entrepreneurial activities

This phase can also be characterized by a decline in industry engagement. Although the 1000 roofs program had been initiated in this phase, the PV market was still not booming and developed slower than thought. This led a number of industrial cooperation's to stop their activities in the PV sector and sell their operations to others (Bruns et al., 2011). For example, AEG dissolved and partly flowed into Daimler as Telefunken Systemtechnik, which later merged with MBB to DASA (EcoAlign, 2010).

Silicon

In 1994, ASE (Applied Solar Energy) emerged as a merger of the PV projects of NUKEM (started in 1979) and the PV research activities of DASA (which emerged from AEG and MBB). In the same year already, ASE acquired the solar division of Mobil Tyco Solar Energy from the USA (Bruns et al., 2011). By this, ASE got hold of the EFG (Edge-defined Film-few Growth) technology which was developed at Mobil Tyco Solar in 1973 (Bruns et al.,2011). This growth process had a number of advantages, for example the reduction of the amount of post-growth processing and machining that was required (Nunes, 1998). Through the consolidation of different projects, early crystalline silicon projects from AEG, NUKEM and Mobil Solar came together in ASE (Bruns et al., 2011). ASE covered a range of PV applications such as solar cells from space to water pumps and PV facades to hybdrid systems (PRNewswire, 1994).

Thin Film

The Centre for Solar Energy and Hydrogen Research (ZSW) started in 1993 with the upscaling of the CIS technology and with the development of a process where large areas could be manufactured in-line, and the line was subsequently constructed (Powalla et al., 2005). In the beginning of the 90'ies, pilot projects using thin film technology were set up by subsidiaries from large industrial or energy companies, such as RWE, Siemens, ARCO and DASA. For example, Siemens began a 3 year subcontract in 1991 with the overall goal of manufacturing a large stable 12.5 efficiency CIS module by techniques that were scalable and low-cost on a cheap substrate (NREL, 1999).

Siemens discontinued its developments in 1994 in a-Si technology and focused on CIS (Bruns et al., 2011). ASE, besides bringing together earlier crystalline silicon technologies through the merger, was also active in thin-film development, which it acquired through MBB (the aerospace company). MBB in the mid 80's failed in a joint venture with NUKEM, and it was subsequently integrated into another form in DASA in 1989, and after that as said into ASE (Bruns et al., 2011). In the 90's the Battelle institute in Frankfurt (where the CdTe thin film technology originated in Germany) closed down, and the scientists from the former institute founded ANTEC Solar Energy GmbH, a company with the aim of producing CdTe based thin film solar cells (Bruns et al., 2011). This company went bankrupt later on in 2002. Phototronics was an early company, set up in the previous period, that started a pilot line for a-Si cells in 1991.

8.2 Knowledge development

8.2.1 Learning by searching (R&D)

In this phase as well, research on PV got high levels of funding (Bruns et al., 2011), which can be seen in figure **X**. The governments' 3rd Energy Research Program was running (from 1990 to 1995), and was focused on lowering the production costs of PV cells, increasing the efficiency, development of thin film cells, optimization of systems, applications engineering and funding pilot installations (Bruns et al., 2011). There is evidence from (authors own) analysis of papers through Scopus that industrial research interest seemed to decline in this period, while research institutions started to do more research (see figure 8.1, mind the different scales on both horizontal axes).

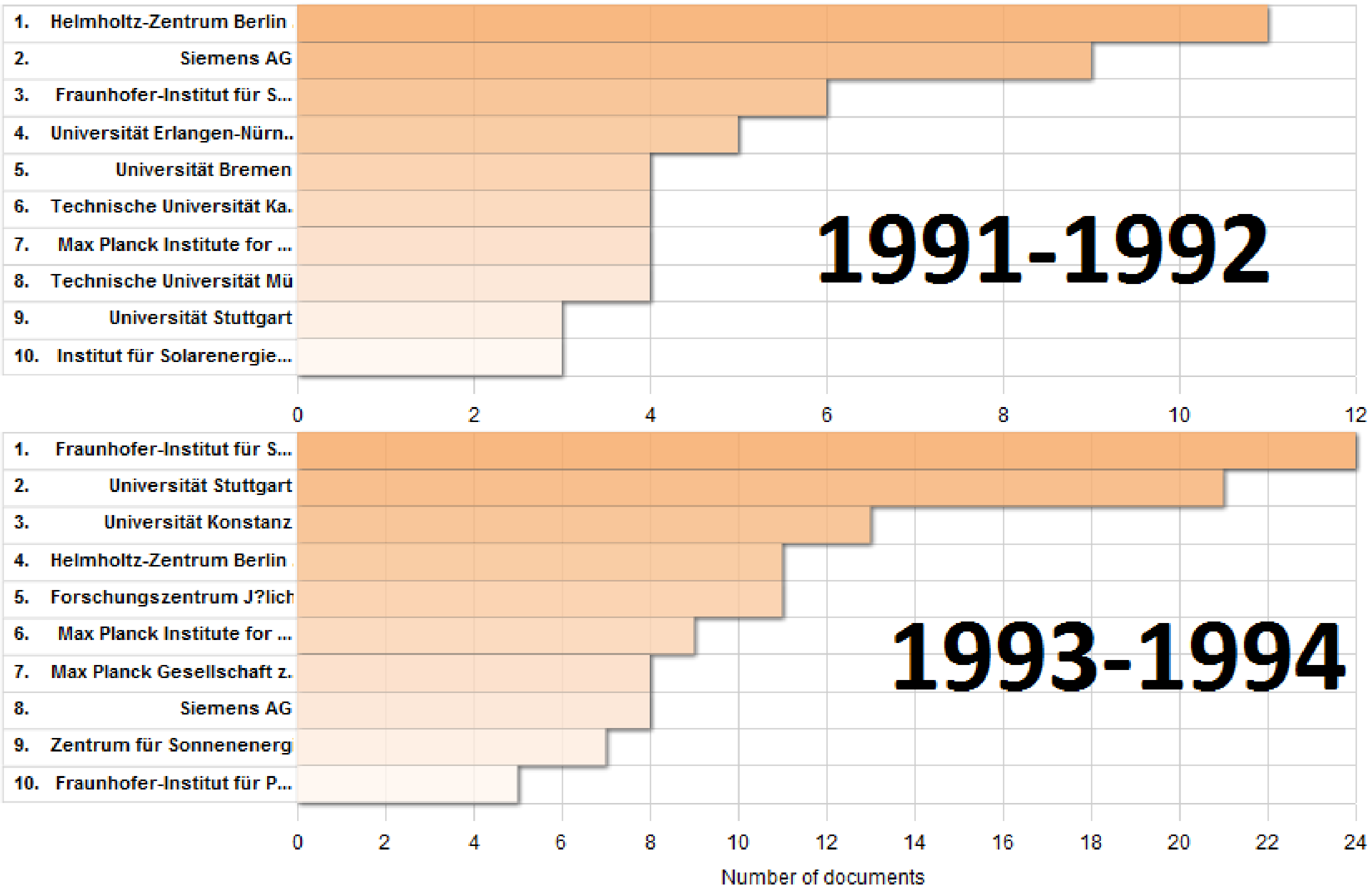


Figure 8.1: Numbers of German papers through search on scopus (" solar cells") from different parties in the period 1991-1992 and 1993-1994

In figure 8.1 it can clearly be seen that the research picked up, which is indicated by the overall amount of papers that increased. This increase came from research institutes rather than from industry, as Siemens AG even produced less scientific papers. Most of the papers published in this period were on thin film technologies, which also seemed to be the main interest of most research institutes.

Silicon

There were some institutes active in c-Si research in this period, as is indicated by a document describing a co-operative research project in Germany on defects in multi crystalline silicon for solar cells (DIXSI, 1990-1996) (Eyer & Reis, 1992). The ultimate goal of the project was to get more insight into the influence of these defects on the efficiency, so that the efficiency can be subsequently increased, and thus this co-operative research project can be categorized as basic research. The document lists ten institutes and six industrial firms involved in the co-operation. It can be clearly seen that the research institutes involved (for example the Fraunhofer institute) were focused on more basic research, whereas industrial partners (e.g. Siemens and ASE) were focused more on supporting with materials, manufacturing, measurement and discussing of results. The research project was completely funded by the BMFT (DM 8 million).

From patents it is clear that Siemens was conducting research into c-Si at this time, although publications were scarce. For example, a patent filed in 1994 focuses on (the production of) a solar cell having a finely structured front side contact for improved efficiency and less complicated manufacturing (Patent Genius, 1994). Thus it can be seen that Siemens was both doing research to improve the cell itself (e.g. quality, effiency) as well as the production process (e.g. less time and costs). That Siemens AG did patent this invention, but did not publish on c-Si technology in scientific papers, could be due to the fact that the c-Si technology at this time was more mature and Siemens was thus less in need of cooperation.

Furthermore, also a search on Scopus (“crystalline silicon solar”) revealed a number of different institutes active in c-Si research. Some of the main contributors will be highlighted.

In this period, the Fraunhofer Institute was one of the main contributors to PV research and one of its points of focus was c-Si cells. This is also evident for example from a conference paper from 1994 in which a record value for c-Si efficiency is measured. An experimental study is presented of the systematic variation of certain variables (e.g. junction depth and sheet resistivity) and its effect on efficiency in order to optimize these parameters (Sterk et al., 1994). The research conducted at the Fraunhofer Institute seemed to be primarily of a basic nature.

Also the University of Konstanz was involved in c-Si research, in fact its’ main (although not exclusive) focus seemed to be on c-Si wafer technology. The research done here seems to be more of an applied nature. For example, a paper appeared in 1994 which describes a novel concept on producing high efficient and light weight c-Si solar cells (Willeke & Fath, 1994).

Another main contributor was the Max Planck Institute, which focused on basic c-Si research, for example on effects of thinning cells on the open circuit voltage (Brendel & Queisser, 1993). Thinner cells at this time were apparently considered important by the institute to lower the cost.

Also the HMI was active in c-Si research in this period as is evident from a paper from 1992 which is of a basic nature (Smestad et al., 1992). Although only one paper from the institute could be found on c-Si in this period, it was cited relatively much (37 times).

c-Si research at this time was supported by the Ministry of Research and Technology.

Miscellaneous

In 1992 a paper appeared on research done by Volkswagen AG on the application of solar cells on car roofs. It was found that solar cells could contribute significantly to reduction in fuel use, as well as aspects related to comfort (Grundmann & König, 1992). This was part of a research project of the European Commission, indicating its support for exploration of a variety of topics on PV application.

Thin film

a-Si

The research on a-Si picked up in this period and around 65 papers from German origin on the topic were published. Table 8.1 provides an overview of the main contributors.

Tabel 8.1: Institutes active in a-Si research together with the number of papers in the period 1991-1994

Institute	# papers
Siemens AG	14
Julich Research Institute	10
TU Kaiserslautern	8
TU Munchen	6

It can be seen that Siemens was a main contributor to research on a-Si PV at this time. Topics were both basic and applied. An example of basic research was research on surface recombination in a-Si solar cells, and an example of more applied research can be found in the manufacturing of large are single junction a-Si:H modules with a higher efficiency. It was furthermore recognized that a-Si would have to find different markets where high performance (i.e. high efficiency) was not a priority, i.e. in calculators, remote applications etc. in order to compete with c-Si cells (Krühler, 1991). Processing techniques, patterning and packaging appeared to be sufficiently developed at this time, however there were still problems such as the degradation problem and the material quality, which hamper the performance of the cell and make it less efficienct (Krühler, 1991). Furthermore, Siemens AG in this period was clearly still expecting much from research on a-Si as is indicated by the fact that most of their found papers in this period on solar cells are on a-Si. Siemens was both active in basic and applied research on a-Si. While a-Si was already an applied technology (e.g. in calculators), the basic research done in this period indicates that the lower efficiencies of a-Si cells in comparison with c-Si cells were considered as a significant problem that had to be overcome, apparently suggesting that a-Si PV was envisioned to be more than just a PV application in calculators and so on. However, not only efficiency was an issue with regard to a-Si cells, but also their manufacturing costs as is indicated by paper where the central issue is to use a novel deposition method in order to get to higher efficiencies, while at the same time using pilot production equipment (Bauer et al., 1993). This paper however also shows that Siemens at this time was not yet ready for large scale market introduction.

A main contributing institute at this time was the Julich Research institute. An interesting observation with regard to a-Si research in this period is that in the period 1991-1992 no papers on PV appeared from the Julich research institute, whereas in 1993-1994 eleven papers on a-Si appeared, all describe basic research. This indicates the growing interest into a-Si research.

The Max Planck Institute at this time was also a main contributor to PV research involved in a-Si research, although it did not seem a main focus.

Research on a-Si was also supported by the Ministry of Research and Technology, e.g. Kusian et al. (1991).

CIS

In this period about 24 papers from German origin appeared on CIS solar cells. An overview of some involved institutes is given in table 8.2.

Table 8.2: Involved institutes in CIS R&D in Germany in this period.

Institute	**# papers**
University of Stuttgart	13
Hahn-Meitner Institute	6
Siemens	2

The University of Stuttgart was active in the field of CIS research as is indicated by a -conference paper from 1994 which shows the potential of an alternative method of deposition (Hariskos et al., 1994). Furthermore, analysis of search results on Scopus ("solar cells") in this period shows that the University of Stuttgart was one of the most important contributors in this period to PV research and that over half of their research activities were devoted to CIS cells. This shows that apparently CIS cells were considered as having favorable properties for solar energy conversion, which is confirmed by the recognition in that time that CIS semiconductor material has a bandgap that almost perfectly matches the optimum bandgap for conversion of solar energy (Walter et al., 1992).

In this period, the Hahn-Meitner Institute, one of the main contributors to PV research at this time, picked up the development of CIS solar cells (Sulfurcell, 2011). A significant portion of the papers appearing from the HMI on PV were dedicated to CIS cells. The research done by the HMI on CIS was of a very basic nature.

From industry, Siemens was also a contributor to CIS research in this period, although its focus was more on a-Si cells. The research was of a basic nature, and furthermore supported by the Ministry of Research and Technology, e.g. see (Riedl et al., 1994).

GaAs

In this period Telefunken System Technik was active in the field of GaAs PV as is indicated by a joint paper with the University of Stuttgart that appeared in 1992 which describes rather basic research on AlGaAs layers and their optical and electrical properties (Dieter et al., 1992). The research was supported by the BMFT.

8.2.2 Learning by doing

Supporting technologies

With regard to inverters, at the time of the 1000 roofs program it became clear that large central inverters should be used, as well as that PV systems should be divided into a number of electrical strings, to which the inverters should subsequently be connected. This would lead to a lower risk of a malfunctioning system (Bruns et al., 2011).

8.2.3 Learning by using

Silicon

In this phase, the 1000 roofs program was running. The main goals of this program seemed not be market creation, but rather to learn by using and to facilitate contextual aspects. Four goals of the program can be identified: To gain know-how on installation, to optimize the components of the system, to stimulate users to adapt their electricity use to the pattern of PV energy generation and to harmonize architectural aspects with construction aspects and the use of roofs for power generation (Erge et al., 2001). Thus the program was accompanied by a measurement analysis program. This was done in order to get experience with the operation of PV systems, through identifying weak spots of system design and installation, as well as monitoring the actual output of electricity (Kiefer & Hoffmann, 1994). The program was headed by the Fraunhofer Institute for Solar Energy Research (FhG-ISE) in collaboration with IST Energietechnik and WIP (Wirtschaft und Infrastruktur Planung) and would continue until 1997 (Imamura, 1994). The measurement analysis program consisted of two parts: The S-MAP project for each system and the more intensive I-MAP project. In the S-MAP project, three values were measured for each and every PV system: Inverter output, and energy into and out of the grid. In the more intensive I-MAP program, 100 plants would be evaluated in more detail through a modem connection from the PV system to the FhG-ISE. Different variables would then be stored and remotely monitored (e.g. besides the data also coming from the S-MAP, in addition the temperature of the ambient air would be measured as well as that of the PV module, amongst other variables) (Imamura, 1994).). Important operational issues were identified, such as the significant effect of the number and frequency of system failures on the annual yield, and the causes of system downtime (Kiefer & Hoffmann, 1994). But also non-technical issues were identified, such as information on actual costs per part of the system, and what could have been a more suitable remuneration rate for potential future programs, as the program could only fund a limited amount of systems, while these systems were largely purchased by segments of the population (e.g. engineers, doctors, physicists etc.) that would probably have accepted a lower remuneration (Imamura, 1994). Furthermore rules and regulation for installation and conditions for the feeding of decentralized power into the grid emerged (Erge et al., 2001). In my view this can also be classified as learning by using in an institutional sense, because from the 1000 roofs program lessons were learned on more appropriate regulation and condition, which resulted in these new institutional measures.

8.3 Knowledge diffusion

Silicon

Outside of the 1000 roofs program collaboration also took place between university and industry, for example by the University of Konstanz and DISCO Hi-Tec Europe GmbH on the use of particular equipment needed for etching (Willeke et al., 1992).

Another example of cooperation on c-Si research is the DIXSI project mentioned earlier, which involved ten research institutes and six industrial partners on the topic of defects in micro crystalline silicon for solar cells (Eyer & Reis, 1992). It seems that the main research work was done in this co-operative project by the research institutes, and that the industrial partners had more of a supporting role (e.g. manufacturing, measuring). Although it is beyond the scope of this thesis to provide a detailed analysis of the sub topics researched by the institutes, it is clear from scanning these subtopics that the activities of the institutes in the project were closely coordinated. This is due to the fact that practically no topic is researched simultaneously by two institutes, except that if it is, it is done through a different method. This suggests strongly that knowledge diffusion must also have taken place, as such a coordinated division of subtopics under the institutions can only give a meaningful result if the different findings are compared and put together. The comparability of results was partly ensured through distributing the same base materials over the different partners (Eyer & Reis, 1992). Some significant results were gained, although there were still many open questions on the topic at the end of the project.

Thin film

a-Si

In this period Siemens was active in basic research on a-Si together with the Technical University in Munich, which is indicated for example by a paper from1993 (Ostendorf et al., 1993).

CIS

Furthermore, Siemens AG was cooperating with Max Planck Institute for Biochemistry on basic CIS research, as is indicated by a joint paper (Riedl et al., 1994).

Also cooperation took place through the EUROCIS consortium, a European consortium on CIS research made up by twelve laboratories from the European Communities (Shock, 1994). It had already appeared that CIS was a material with good potential for PV applications, and significant progress in device performance in laboratory setting were already achieved, however upscaling was still a challenge. The cooperation focused on enhancing basic understanding of CIS as well as investigating ways for large scale manufacturing, and thus had a basic and applied focus (Shock, 1994). Two institutes from the consortium were German, namely ZSW from Stuttgart and the University of Stuttgart. The ZSW played a leading role as technical coordinator and was involved in sub-module development, whereas the University of Stuttgart focused on window deposition as well as modified and new absorber materials. The consortium resulted in new developments for processes and devices and high efficiencies were achieved. The research was furthermore supported by the CEC (Commission of European Communities), and the University of Stuttgart was supported by the BMFT.

Related to the consortium but within a national context, when the University of Stuttgart produced a 1cm^2 CIS cell with an efficiency of 17%, CIS technology became more attractive which resulted in a cooperation between IPE and ZSW (The Centre for Solar Energy and Hydrogen Research Stuttgart founded in 1988). This cooperation was aimed at setting up a pilot-scale plant for CIS technology (30cm x 30cm modules), with the mid-term goal of developing technology suitable for mass production (120 x 60cm modules) (Wirtz & Janssen, 2010). Thus, in 1993 the ZSW picked up the challenge of up scaling the CIS technology and develop the technology needed for large-area in-line production and the monolithic integration of modules (Powalla et al., 2005).

The EUROCIS consortium and the German cooperation within it of ZSW and the University of Stuttgart proved to be the prelude to later developments of Würth solar and its pilot production of CIS solar cells which will be discussed in a later chapter.

1000 roofs project

In this period the 1000 roofs program was running, which resulted in collaboration between all 16 involved states as well as several institutes (Imamura, 1994). Since different institutes fulfilled different functions which were not capital related but rather knowledge based, as can be seen in table 8.3, inevitably this must have fulfilled a function of knowledge diffusion. Without this, the different parts of the project could not possibly fit together.

Table 8.3: Overview of involved parties in the 1000 roofs program together with their function (Imamura, 1994).

Name	Function (1)	(2)	(3)	(4)	(5)	(6)	(7)
Designated office in each of 16 federal states	X						
FhG-ISE (Fraunhofer Institut für Solare Energiesysteme), Freiburg				X		X	
FZR (Forschungszentrum Rossendorf), Dresden		X					
ISET (Institut für Solare Energieversorgungstechnik), Kassel				X	X		
ISFH (Institut für Solarenergieforschung), Hannover	X	X					
IST Energietechnik, Augsburg							X
JRC (Joint Research Centre), Ispra (Italy)						X	
TUV Rheinland (Institut für Umweltschutz und Energietechnik), Köln			X	X	X		
WIP (Wirtschaft und Infrastruktur Planung), München						X	
ZSW (Zentrum fur Sonnenenergie- und Wasser-stofforschung), Stuttgart		X			X		

(1) Contract administration.
(2) Examination of proposals selection, and inspection PV of plants.
(3) Standards for installation.
(4) Testing of components.
(5) Conducting special courses.
(6) Plant monitoring and evaluation.
(7) Design/installation of monitoring equipment.

8.4 Guidance of search

In this period the 1000 roofs program was running. PV at this time was considered to be a viable option on the long term for CO2-free generation of power, and the German Federal Government at this time had the intention to reduce CO2 emissions by 25% by 2005. This was perhaps one of the main motivations for the 1000 roofs program (Imamura, 1994). But not only was the 1000 roofs program partly the cause of a vision, it resulted in a vision as well. The 1000 roofs program seemed to have created a kind of sense of sunk costs: In the period the program was running many believed that there should be a follow up program, sustaining the support, in order to not damage the momentum that was developed during the program (Imamura, 1994). This in turn led to lobby activities and so on, described in a later part of this thesis.

There was also government support for research on PV technologies in general, as is indicated in the previous section on knowledge development. However it was not explicitly found how this was divided amongst the different PV technologies. Nonetheless some idea of this division could be gained based on the papers on the different topics (given certain assumptions). For example, a search in Scopus shows that most papers at this time were focused on thin film technologies (e.g. a-Si and CIS), and considerably less on c-Si technology. Furthermore, under the heading of "Acknowledgements" in the papers funding from BMFT under a certain contract was mentioned if applicable. With regard to silicon wafer technologies, it was found that about half of the papers mentioned funding from BMFT, whereas almost every paper found on thin film technology mentioned funding from BMFT. Combining this with the earlier fact that papers on thin film PV numbered significantly more than papers on c-Si technology, this suggests that thin film PV was granted more funding at this time than c-Si technology, although both were definitely funded. The spread in support for the different PV technologies in any case indicates that the government was pursuing a strategy of creating diversity in the PV market, but thought that thin film PV would be the future of PV or simply needed to catch up with c-Si technology.

8.5 Market formation

An important aspect of market formation in this period was the 1000 roofs program, which was launched September 1990 and initiated by the Federal Research Ministry. The program was financed by the Federal Government and the states. The program focused on private households and their power generation. Although the program came down to large scale testing, it was conceived by many as the first stages of the market launch in Germany (Bruns et al., 2011). Indeed, the program was initiated to create momentum for the PV industry, as the parliament had appealed to boost support for R&D in renewable energies earlier in the context of the Chernobyl nuclear disaster that happened earlier(Bruns et al., 2011). It was, besides generating demand for PV, a demonstration program which was to show that decentralized feed-in from PV systems did not pose a problem. The actual way the funding took place was that the Federal Government and states would pay up to 70% of the investment costs in the PV systems, rooftop systems that were between 1 and 5 kW in capacity (Bruns et al., 2011). The utilities were subsequently legally obliged to purchase the electricity fed into the grid at a rate of 0.166 DM/kWh (Imamura, 1994). Originally up to 1500 roofs would have PV systems installed, but this was later extended to 2,250 grid connected PV roof systems in order to cover the federal states of former East Germany (Imamura, 1994). Furthermore, until 1991 it was only allowed to purchase modules from German manufacturers (i.e. Siemens, DASA and Nukem) (Imamura, 1994). This resulted in a more attractive starting situation for German PV firms, which could have had a motivating effect on German firms to keep going in the PV business. The duration of this rule was however short in comparison to the duration of the program. Within the 1000 roofs program, it was not only the subsidies of up to 70% that contributed to the home owners purchasing a PV system. It was also possible to involve these private home owners through the environmental friendly “green” image that they would acquire through putting a PV system on a clearly visible place on their roofs. (Bruns et al., 2011). Also a contributing factor was the long lifetime of a PV system (over 20 years), which was in line with the long term expectation of those building their own homes and also helped to engage private house owners in generating electricity through solar cells (Bruns et al., 2011). Although the 1000 roofs program was not explicitly focused on one type of PV technology, in practice it only suited the silicon wafer technology due to the fact that c-Si technology had significantly higher efficiencies than thin film technologies such as a-Si, and that this technology had been operating in some terrestrial applications as mentioned earlier and thus had a reference. Thus the 1000 roofs program created market growth for silicon wafer technology rather than for thin film cells

The interest in the program turned out to be higher than the 1000 roofs program could accommodate. For example in the state of Baden-Würtemberg over 10,000 proposals were received by the regional office, of which only a fraction could be accepted due to the limited funds (Imamura, 1994). Eventually, 50 million euro was granted, the installed capacity of the systems equaled 4MW and the last system was installed at the end of 1995 (Bruns et al., 2011). Internationally this program was considered as the largest PV test project, and it resulted in the development of new supporting technology (i.e. inverters) and it led to new entrants in the form of electrical installers (Jacobsson et al., 2010). No immediate follow up program for market introduction was planned however, due to the fact that the program was an R&D project and was labeled as such (Bruns et al., 2011).

Of course it can be questioned whether or not the 1000 roofs program in this period created a small market space for German PV manufacturers or for foreign firms. It seems that it did create a small niche for specifically German producers, since more than 84% of the installed modules were from German firms (Especially Siemens) (Kiefer & Hoffmann, 1994).

During the program, supplementary programs from the states were initiated. An example of this is the state of Baden-Württemberg, which subsidized 220 PV systems by 35% of the costs. Other examples are Berlin, Hessen and Saarland which provided grants for 70%, 50% and 50% of the costs respectively. The duration of these programs however was limited and thus their influence has only been supportive rather than having a key impact on the diffusion (Bruns et al., 2011).

Also, in 1991 the feed-in payments under the Electricity Feed-in Act (StrEG) started, initiated by the Federal Environment Ministry, although these were much too low due to the high costs involved at that time. (Bruns et al., 2011). The compensation per kW under the act was at least 90% of the average revenue per kWh that utilities had from the sale of electricity to their final customer. Even though the costs of PV generated electricity were 1 euro/kWh, the act resulted in payments of about 10 cents/kWh in the 90's (Bruns et al., 2011). Thus the impact of the act was small, but nonetheless it had a positive influence on the developments: It created an important condition, as now the PV systems had a guaranteed connection to the grid, which was an important contextual condition for the further development of the technology, and it communicated a positive signal towards the PV sector (Bruns et al., 2011).

In table 8.4, the totaled installed capacity in Germany is shown (Bruns et al., 2011).

	1990	1991	1992	1993	1994
Installed capacity (MWp)	1	2	3	5	6
New installations (MWp)		1	1	2	1
Growth on previous year		100%	50%	67%	20%
Market stimulated by:		1,000 Roofs program			

Table 8.4: Installed capacity of PV systems from 1990 to 1994 (Bruns et al., 2011)

As can be seen, the growth during the period of end 1990 to end 1994 is 5 MW which is approximately equal to the installed capacity under the 1000 roofs program, and the growth can be primarily attributed to this program (Bruns et al., 2011). The costs were still high at this time: 1

euro/kWh for the generation of electricity through PV and over 10,000 euro/kW for the system price (Bruns et al., 2011).

Another measure implemented in this period was the Full Cost Rate (FCR), also called cost covering payment. Under this proposal, private house owners are equal to utilities when it comes to producing electricity: They generate electricity by PV which is feeded into the grid, and for which the subsequently get remuneration (i.e. for every PV generated kWh they feed into the grid), with which they can finance the PV system (SFV, 2001). This will be further discussed under the next phase. These Full Cost Rates, which were initially introduced by the local city councils, were first implemented in the cities of Aachen, Freising and Hammelburg in 1993 (SFV, 2001). Since the idea for this cost covering payment originated in Aachen, it has been called the Aachen model (Bruns et al., 2011).

Thin-film

At this time, a-Si technology appeared to have a significant market share of 26-32% (Bubenzer et al., 1994), which was more than other thin film technologies such as CdTe and CIS. This should not be understood as a large market in absolute terms: The total installed PV capacity in Germany at this time was still small and large scale power generation through PV did not yet start. a-SI cells could not compete with c-Si cells on efficiency, which means that other markets for a-Si were envisioned such as battery chargers, automotive systems and walk lights (Bubenzer et al., 1994). It seems that in this time the government was not supporting the market formation for thin-film technologies as it did with c-Si through, for example, the 1000 roofs program.

Supporting technologies

It was only when the 1000 roofs program emerged that serial production of transistor-based inverters became feasible, which was necessary to guarantee grid connection despite the fluctuating power generation from PV modules (Bruns et al., 2011). Thus, since 1992 the number of suppliers of inverters increased (Imamura, 1994). The costs of inverters for PV were quite high (1 euro/W), and the efficiency was about 90%; this implied that on a 3kW system, just the inverter cost 3000 euro (Bruns et al., 2011). However the program did motivate the further development of inverters and the production of inverters for low power ratings. The majority (if not all) of the manufacturers involved were German, with SMA having almost half of the market share (Kiefer & Hoffmann, 1994).

8.6 Resources mobilization

At this point in time it is clear that R&D on PV technologies was mainly conducted by large established firms, such as the ASE group and Siemens, or research institutes (e.g. Fraunhofer Institute) that got funding from the BMFT for their research. It thus seemed that there was sufficient funding to conduct research on PV.

With regard to physical resources, at this early time the demand from the PV sector for raw materials was still relatively small and there were no indications found of any material constraints.

8.7 Advocacy coalitions

In this period Eurosolar was lobbying for the 100,000 roofs program and a first draft was presented in 1993. The initiator (and founder) explains: *"My argument was: If we wanted to gain more support for the solar perspective in politics and society, big steps would have to be demanded. After all, only few* *people are interested in small steps, and the underestimation of solar energy could not be overcome that way."* (Palz, 2010a). Also a book was published by the initiator, "A Solar Manifesto", and the argumentation convinced the youth department of his party which subsequently started a solar campaign and made the book required reading. The book was not on technical aspects of solar energy, but on policy needed for solar energy to succeed. The book furthermore became a bestseller in Germany and gave a political expression to the support for solar energy (Palz, 2010a). Furthermore, it revealed the (lowest) level of promotion of renewable energies in politics and the (highest) level of promotion for nuclear and fossil energy, and it showed the why and how of resistance towards renewable energy. An example of this was the "technological pessimism" towards renewable energies, in stark contrast with the technological optimism "in favour of any other technology", according to the initiator (Palz, 2010a). Subsequently, quite some players in politics, companies and scientists were inspired by the work (Palz, 2010a). Even though there was no possibility yet for implementing the 100,000 roofs program, more and more activities were initiated on a local-government level. An example of this were "solar clubs" which were set up, such as the solar-promotion club (the SFV) in Aachen, North Rhine-Westphalia. The SFV called for a cost-covering payment according to the principle of the feed-in law, for those people that had a PV installation. This plan was subsequently picked-up by the city of Aachen in 1993/1994, and could not have been realized without the efforts of the SFV, as there was considerable opposition from the municipal utility company STAWAG (Bruns et al., 2011).

8.8 Conclusion

Clearly in this period there was not yet much growth in the PV industry, which was not possible without a growth of the market. Although mergers took place as well as strategic reorientation, new industrial entrants were scarce. This points to a lack of industrial interest which can be explained by the lack of growth of the market and the efficiencies which had not fulfilled expectations. R&D and development however did seem to pick up in this period, but not from the side of industry. Rather, research institutes engaged in basic research on thin film technologies, more than on crystalline silicon technologies. The a-Si thin film technology was most popular in this regard, from the perspective of research institutes as well as from the perspective of industry. But while research was focusing more on thin-film, and in particular a-Si, and while the government (BMFT) employed a strategy of supporting a diverse set of PV technologies, other functions were again favoring the c-Si technology. For example the 1000 roofs program was at this time only relevant for c-Si technology, due to the fact that it had high enough efficiencies at this time to generate enough electricity on a limited (roof) surface, and it had been shown to work in such systems as well. Furthermore the feed-in payments under the StrEG and the Full Cost Rates both were only relevant for house owners with PV systems on their roofs, which were practically only c-Si based as mentioned earlier. Although these initiatives had only a small impact in absolute terms, they did give positive signals to the PV sector and they created an important framework condition: The connection of PV systems to the grid. This is due to the fact that in order for PV systems to become economical and experience a boost in terms of diffusion in later periods, they would be dependent upon remuneration from feed-in payments which would be impossible without connection to the grid. Furthermore, advocacy coalitions had laid a basis for what would later on prove to be essential policy instruments. Thus even though growth of the market was small, important steps were taken that would facilitate large scale diffusion later on of c-Si cells. The variety of research conducted furthermore shows the uncertainty in what thin film PV technology would turn out to be dominant in the future. It thus seems that thin-film cells PV technologies were engaged in a sort of sub-competition of their own with regard to research funding.

9. 1994-1998

9.1 Entrepreneurial activities

In this period there was not much growth, and it was very much fluctuating. This was primary due to the absence of a follow up program to the 1000 roofs program from the previous period, which implied a halt of funding and subsequently hampered the introduction of PV products, as no self-supporting market had been formed (Bruns et al., 2011). Nonetheless, the phase was not without activity. Eurosolar (a PV interest group) had proposed a 100,000 roofs program in 1993 as a follow up to the 1000 roofs program (which did not lead to a take-off for PV in Germany). It seems that after the 1000 roofs program by 1990 had not created significant incentive for many entrepreneurs to enter the solar market, but the advent of the 100,000 program seems to have generated at least some entrepreneurial activity in the subsequent years. Since 1996, the German PV industry association was working for the realization of this program (Jacobsson & Lauber, 2006).

Silicon

By 1996 only Siemens and ASE (two major German module manufacturing companies) were active; they were active in a broad field of PV technology, such as crystalline silicon, a-Si, CIS and CdTe (Bruns et al., 2011).

However a number of new companies was about to enter, probably due to the coming policy prospects mentioned earlier. In 1996, Solar Fabrik starts as module manufacturer and Sunways launches its inverters onto the market (Sunways, 2011). In 1997, Ersol Solar (later taken over by Bosch Solar) was founded, as well as PV silicon, a silicon wafer producer. SOLON was founded in 1997 and engaged in planning/development of production for solar cells and modules, and went public in 1998, being the first listed PV energy company in Germany (Bruns et al., 2011), (Civic Solar, 2011). Furthermore, by the end of this phase in 1998 SolarWorld was founded. It's core business covers all stages of the value chain (i.e. from silicon to module or even solar power plant) and it emerged within a few years to be one of the largest integrated PV companies (Solarworld, 2011).Also, the first companies specializing in a narrow field appeared in this period such as PV silicon, which was founded in 1997 in Erfurt and focused solely on manufacturing wafers by sawing silicon ingots (Bruns et al., 2011). The number of full time labor places increased from 1400 in 1995 to 1800 in 1997 (Erge et al., 2001).

Siemens at this time in this period had already started production in the US (Lauber, 2005). ASE in this period had acquired Mobil Solar and was thus able to start production in the US. To start production in Germany for ASE was not attractive without any prospects of a market; only when the 100,000 roofs program was guaranteed, ASE decided to build a 20 MW wafer manufacturing plant (with the technology acquired from Mobil Solar) in Germany which started production in mid-1998 (Lauber, 2005). In the same period, Shell entered into the German solar market in 1998 by investing in a new 9.5 MW production plant. The investment of ASE and Shell expanded the German solar industry (Lauber, 2005).

However for the bulk of this period it can be said that the growth was weak and very much fluctuating. Some large firms started to be less involved or stopped their activities with regard to PV entirely, whereas other new firms entered, apparently spotting potential (Bruns et al., 2011). Thus there seemed to be two opposite developments in this period. The small boom in startups, despite uncertainty with regards to the contextual factors (e.g. the ending of the 1000 roofs program), showed that at least expectations had been created by the 1000 roofs program (Bruns et al., 2011). Also international developments of rising demand were anticipated in countries without a comprehensive supply of electricity, which created positive prospects; at the same time however, the German government stopped funding PV projects in developing countries. This took away an important potential market for the German domestic PV industry (Bruns et al., 2011).

Thin film

As mentioned, two major German module manufacturers (Siemens and ASE) were active in 1996, which focused on silicon as well as thin film technologies such as a-Si, CIS and CdTe. Siemens for example has a number of patents originating from this period in CIS technology which indicates their activity in the field (Markvart & Castaner, 2003). However, the activities of Siemens on CIS in this phase seem to be more focused on research than on introduction to the market. More in general it can be said that in this period the most important thin film technologies (i.e. a-Si, CdTe and CIS) were close to large scale manufacturing or pilot production at this end of this period in 1998 (Dimmler, 1998). This indicates that during this period activities with regard to thin film were more focused on R&D than entrepreneurship.

9.2 Knowledge development

9.2.1 Learning by searching (R&D)

As a general note for this period, it can be seen that research into PV grew, although not without fluctuation, as is indicated by a search on Scopus for German papers ("solar cells") as can be seen in figure 9.1. The decrease from 1997-1998 compared to the number of papers at the maximum in 1997 was relatively smaller than the decrease in 1994-1995 compared to the number of papers at the maximum in 1994. Furthermore in 1999 the amount would start rising again. Thus the dip in 1994-1995 is more significant than the dip in 1997-1998, and can be explained by the 4th federal energy research program (1996-2005) which was about to follow the 3rd one (1990-1995). After the 3rd research program was about to end, it could well be that institutes were waiting for the new strategy on PV funding to be made public, in order to adjust their research topics in line with the government strategy in order to secure funding.

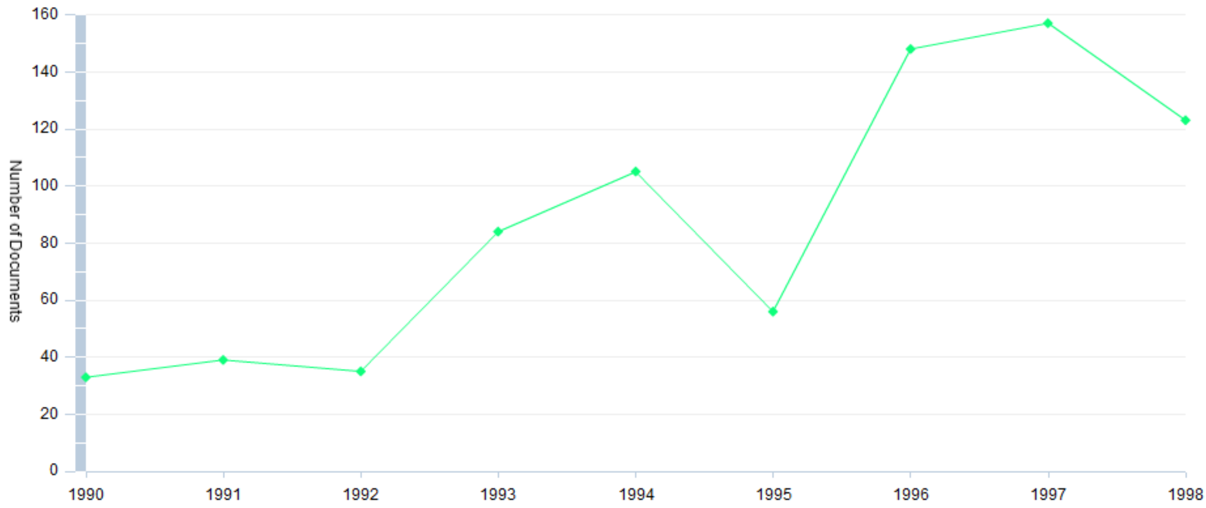


Figure 9.1: Number of papers from German origin on "solar cells" found on Scopus, as an indication of the amount of research that was done in comparison to previous years.

Silicon

The development of the number of German papers on crystalline silicon shows a similar as shown in the previous shown figure as can be seen in figure 9.2.

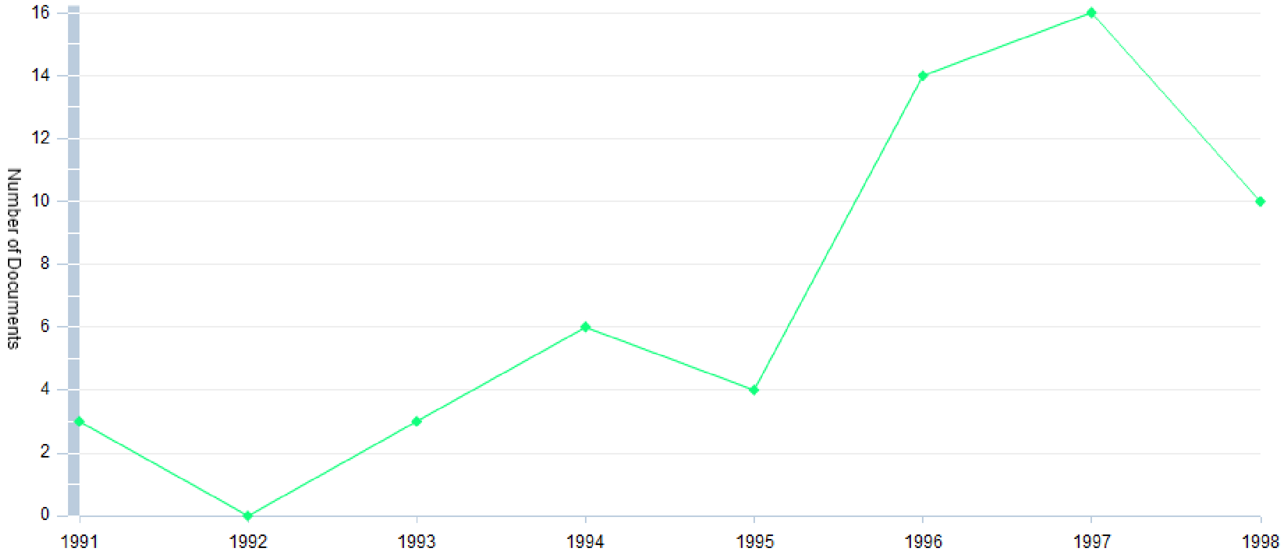


Figure 9.2: Development of papers from German origin in the period 1991-1998 on crystalline silicon solar, taken from Scopus.

An overview of some of the most contributing involved institutes is given in table 9.1.

Table 9.1: Overview of contribution R&D parties in this period in the field of c-Si PV.

Institute	**# papers**
University of Konstanz	8
Fraunhofer Institute	6
Siemens AG	5
Institute of Solar energy Research	5
University of Stuttgart	4

Siemens Solar, as one of the two major German companies active in 1996 in module technology, was conducting research into silicon PV (as well as thin film) in this period as is shown by a number of patents. For example, a patent filed in 1996 describes the production of a crystalline silicon solar cell with an efficiency of over 20% in cost- and material-saving way through the use of a tricrystal (Patent Genius, 1996). Some advantages of the invention include that a tricrystal can be grown more rapidly than other types of monocrystals, the cooling time is reduced and the crucible can be used an increased number of time compared with other monocrystals (which saves time and material). Their research on c-Si is also indicated by a number of papers on c-Si cells. Although the amount of papers from Siemens AG on c-Si is still considerably less than it's papers on thin film PV, in the previous period hardly any papers appeared from Siemens on c-Si technology.

One of the main institutes that contributed to c-Si research is the Institute for Solar energy Research. In the previous period it had a relatively small amount of papers with a focus somewhat on organic solar cells and thin film cells. However, in this period it seems to have definitely focused on c-Si wafer technology and simultaneously increased its research activities as it now became a main contributor to PV research (judging from the amount of articles). The research done at the institute was both applied, e.g. see Hezel & Metz (1998), and basic, e.g. see Schmidt et al., (1997).

Just like in the previous period, the Max Planck institute was a main contributor in c-Si research, and mainly with regard to developing thinner and thinner wafers. The research done by the institute in this regard was both applied (e.g. thin silicon wafer produced by a new process)and basic (e.g. theoretical work on efficiency limits) and also funded by BMFB of the federal government.

Another main contributor to c-Si (thin film) research was the Fraunhofer Institute. The research appears to be more applied than basic, for example on the processing of cells.

Also the University of Konstanz, just like in the previous period, was conducting research into c-Si cells, both applied (e.g. on ribbon growth on substrate silicon) and basic (e.g. evaluation of diffusion length in c-Si cells).

Thin Film

In general, thin film technologies all improved with regard to efficiency as can be seen in figure 9.3.

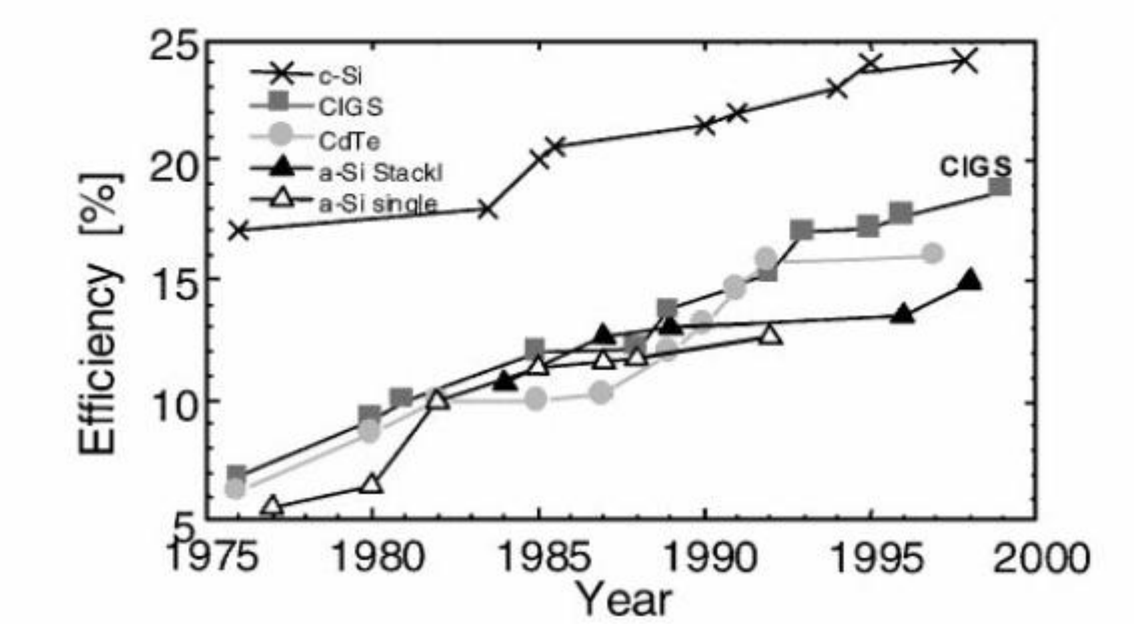
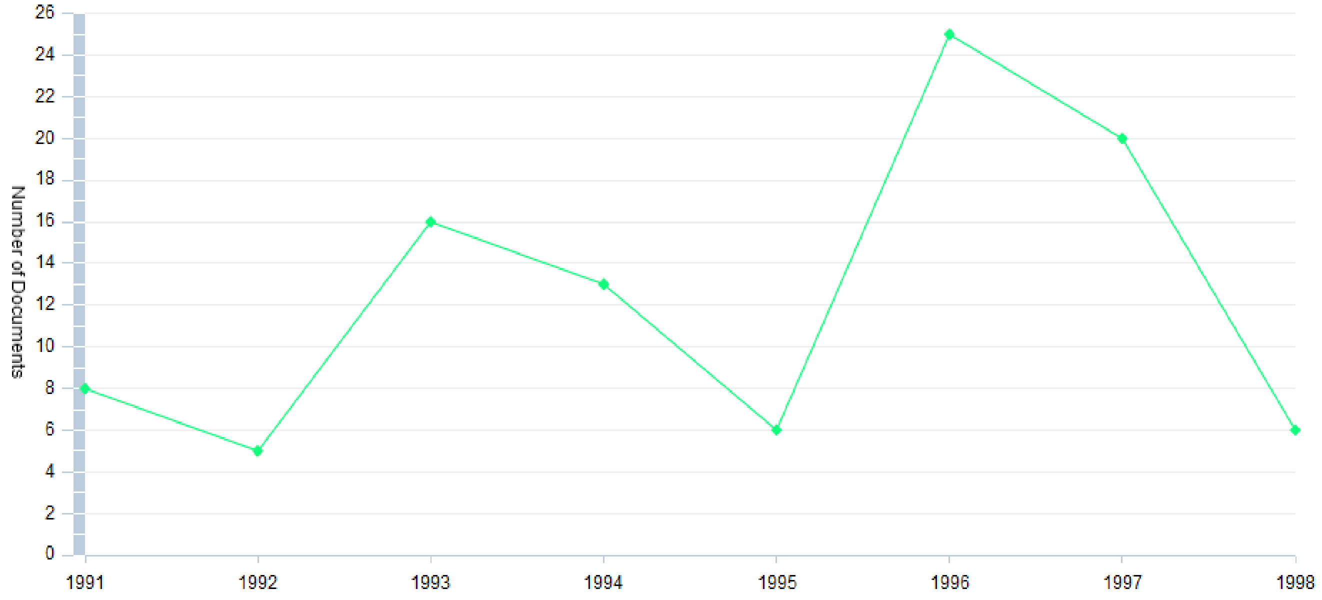


Figure 9.3: Development of efficiencies of different PV technologies over time (Goetzberger & Hebling, 2000).

Although the efficiencies in the figure need not all be from German institutions, the research on PV was already considerably globalized at this time through conferences, papers and so on. This makes it extremely likely that efficiencies over the worlds different research institutions with regard to PV did not differ much, especially in the case of renowned R&D labs.

a-Si

It appears that the same pattern of development holds with regard to papers from German origin on a-Si as shown in figure 9.4 compared the general pattern of development of papers on solar cells shown in figure 9.1.



Figuur 9.4: The number of papers from German origin on a-Si solar cells over the period 1991-1998, taken from Scopus.

In absolute terms, the amount of papers in the period 1994-1998 lies around 70.

An overview of institutions with most contributions in this period on a-Si solar cells along with some of their topics is given in table 9.2.

Table 9.2: Leading R&D institutes in the field of a-Si in this period.

Institution	# papers
Julich Research Institute	29
University of Stuttgart	10
TU Kaiserslautern	6

A main research institute contributing to a-Si research in this period is the Jülich Research Institute. The research done is of a basic nature and also partly focused on heterojunction cells (i.e. a cell with a-Si and c-Si layers in this case), for example see Gall et al. (1997). The research was also partly funded by the BMFB department from the government (which resulted from the fusion of BMFT and BMWB in 1994).

Siemens Solar GmbH was still active in the field of a-Si research in a part of this period (it later stopped as will be pointed out), as is shown by a patent filed in 1995 for a a-Si thin film module (Patent Genius, 1995). An aluminum substrate was used instead of glass, which makes the module more varied in use as a façade element due to the virtually unlimited shapeability. Thin films have a lower efficiency than crystalline silicon cells and therefore need a larger covered surface in order to provide enough electricity. Thus it was proposed that façade elements of glass be coated with thin film cells. Furthermore, window glass is economically priced as a substrate. However, this restricts the use of thin-film to glass substrates, which makes it less functional for the use as a façade element. The invention in the patent referenced earlier solves this by employing an aluminum substrate (Patent Genius, 1995). This furthermore shows that Siemens was active into applied research with regard to a-Si thin film modules. In the previous period it became clear that a-Si had been a focus of the R&D done at Siemens, and now that domestic grid connected application of PV had showed its potential for c-Si cells, Siemens was evidently looking for a way to apply it's a-Si R&D knowledge in this large potential market. Nonetheless, it seems that Siemens stopped its R&D with regard to a-Si entirely later in this period. According to Bruns et al. (2011) this was in 1994, however a last paper from Siemens on a-Si solar cells appeared in 1997, see Smole et al. (1997), indicating that the research on a-Si up until this point did not entirely stop.

An example of research from the other active firm in PV, ASE, on a-Si thin film cells in this period can be found in a patent filed in 1998. The invention resulting from the research relates to a-Si cells where the intrinsic layer is deposited using a heated wire, as well as the apparatus to carry out such a method (Patent Genius, 1998). On an industrial scale, mainly plasma enhanced chemical vapor deposition (PECVD) is used at the time of invention, and this technique is limited in its deposition rate compared to the proposed hot wire method for deposition proposed in the patent. Further patents of ASE in this period seem to be few or absent, which of course does not imply that no research was done. As patents in subsequent years (i.e. from 2000 to 2002) do appear, it seems that it took ASE about 4 to 6 years since its foundation in 1994 to produce the results described in the patents. Another explanation is that they had these results earlier, but decided to wait before filing a patent. This is an option due to the fact that ASE did not start from scratch: ASE as mentioned earlier was a merger from several companies and brought together crystalline silicon research from these companies and also thin film research (e.g. from MBB) flowed into ASE through the merger. Since they already had knowledge on PV technologies, it is reasonable to expect earlier relevant findings, instead of the 4-6 year gap between the start of ASE and the first flow of patents.

CIS

The pattern shown in figure 9.1 also holds for the development of the amount of papers on CIS cells, as can be seen in figure 9.5, which was taken from Scopus by comprehensively searching any German originating paper on CIS solar cells over 1991-1998.

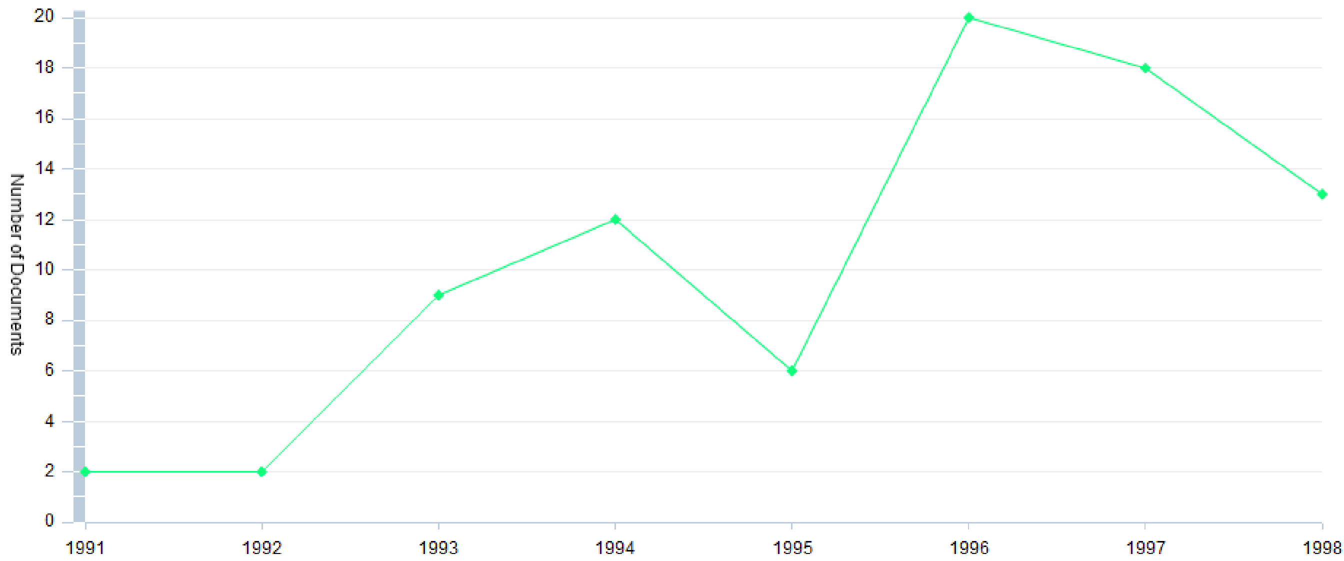


Figure 9.5: Number of papers from German origin on CIS solar cells in the period 1991-1998, taken from Scopus.

A total of around 62 papers were found on CIS during the period 1994-1998 on Scopus. An overview of main contributors is given in table 9.3.

Table 9.3: Contributors to CIS PV research in 1994-1998

Institute	# papers
University of Stuttgart	24
Hahn Meitner Institute	20
ZSW	4

It appears that the R&D from the main contributor on CIS, the University of Stuttgart, was both basic and applied. An example of applied research is the upscaling of the deposition process which was done in cooperation with ZSW. Mini modules were successfully produced with efficiencies of almost 14% and also larger modules of 30cm x 30cm with an efficiency of 10,7%. Furthermore, optimization processes for large area deposition and patterning had just started, indicating that further progress could be expected (Dimmler & Schock, 1998). The majority of papers on CIS was however basic in nature.

In this period, with regard to CIS, Siemens was working on a thin film deposition process that was high-yield and high-throughput, in order to make CIS thin film technology profitable. This was done through scaling up so called “mine modules”, after monitoring, controlling and demonstrating processes. Siemens’ research approach consisted of two tasks (NREL, 1999):

“• Experimentation and development using device structures that exercise all aspects of large area module production.

• Application of statistical process control (SPC) as the discipline to rigorously quantify process reproducibility, and application of statistical methods such as analysis of variation (ANOVA) to rigorously quantify experimental results.”

It is somewhat ambiguous here to make a distinction between learning by searching and learning by doing: In effect Siemens here is actively *searching* and exploring new information (e.g. information on new stuctures and quantitative experimental results), but at the same time learning by *doing*: SPC is done by running the production process and subsequently evaluate the process and correct steps wherever needed. It can be called learning by searching due to the creation of new knowledge (e.g. what are appropriate structures to use, or quantitative experimental results), and it can be called learning by doing due to acquiring skills in production that lead to more efficient production (e.g. improving the production process on the basis of SPC). Perhaps relevant here is the fact that the production of CIS modules here was still in the development stage at Siemens, and thus it could be more relevant to mention it under learning by searching; when a process is already in use in industrial production the focus is not on developing the process, but instead on production and learning is a byproduct of actually carrying out the production process. In contrast, although learning was carried out at Siemens in this phase by carrying out the production process (and subsequently monitoring and controlling it), this was for the sole purpose of learning and not for production.

Also patents from Siemens Solar were registered in this period on CIS technology as mentioned earlier. Furthermore, existing CIS modules and systems from Siemens were being evaluated in an American Laboratory. Module and array performance were studied over time and different parameters were determined. For example, it was shown that CIS is characterized by a strong inverse relation between array power and back-of-module temperature, which is due to the narrow bandgap of CIS material. Furthermore it was shown that the module and array performance was stable over the evaluation period of two years (Strand et al., 1996). This shows that Siemens did not restrict its' research activities to Germany, but made use of international opportunities as well.

9.2.2 Learning by doing

An issue with learning by doing with regard to solar cells is how to know what portion of cost reductions in the end product (which are commonly attributed to learning by doing) can be attributed by learning through manufacturing, and what portion of cost reductions should be attributed to work in the laboratory rather than in the factory. In industries where changes to the actual end product are relatively small and do not amount to large differences in manufacturing costs over time, cost reductions can be more easily attributed to an industry where the product itself is constantly improving and at the same time lowering the manufacturing costs. The reason for mentioning this here is that solar cells present a good example of the latter. For example, the cost of modules is affected by a number of factors, including the output of the modules (which is in turn affected by its size and efficiency), as well as the material costs. Thus, if in the laboratory higher efficiencies are achieved and consequently transferred to industry, this means that the size of the module can subsequently be reduced to achieve the same output, which leads to a lower price eventually. Furthermore, reductions in material costs (which *can* be achieved in the laboratory e.g. in the form of reductions in thickness) also lead to a reduction in the eventual module price. Both examples, however, are examples of results from R&D and cannot be attributed to learning by doing in the traditional sense of improving productivity through regular repetition of a certain activity. Thus a conventional way of looking at reductions in cost, and using this as an indicator, seems not be accurate at all for the case of solar cells.

Another potential issue is be the general nature of information on PV modules; in effect, data that is available on module prices or system prices usually does not distinguish between countries. Thus to attribute learning by doing effects specifically to German firms is not conceptually accurate. This can be solved by assuming that learning by doing in modules is more of a global experience, in contrast to PV balance of system (BOS) costs which includes some local aspects such as labor costs and management (van Benthem et al., 2007).

Thin film

As mentioned earlier, two CIS thin film manufacturing process originated from Siemens Solar Industries and Stuttgart university. In this period, Siemens was working on the demonstration of the performance and commercial viability of its CIS cells (NREL, 1999). In a subcontract, Siemens conducted a project divided into three phases: Demonstration of reproducibility and yield (1), scale-up to large area substrates (2) and demonstration of reproducibility and yield for large-area substrates (3). Evaluations and studies conducted enabled SSI to learn and improve their operation and understanding, and to subsequently get a step closer to industrial production in, for example the second phase: *"As a result of these studies, and advances in understanding the influence of reactor (needed for producing circuit plates) design on performance, SSI designed and built a new large area reactor based on a more direct scale-up of the baseline reactor."* (NREL, 1999). An even more concrete example which indicates how learning by doing take place can be found in phase three: SSI applied SPC (statistical process control, used to monitor and control a process) and Analysis of Variation methodologies through "repeated cycles of learning" during production in order to ensure low process variations (NREL, 1999) What is in fact happening in, for example SPC, is that a variation in the process (which may negatively impact the end product) is detected (thus after use), and subsequently corrected. Thus, this is approach is specifically aimed at learning through conducting the process (i.e. doing) by monitoring and controlling.

9.2.3 Learning by using

Furthermore, in this period a sort of standardization emerged with regard to installation rules, which resulted from the broad-scale tests for residential PV systems which emerged in this period (Laukamp & Bopp, 1996). Also, following the 1000 roofs program, comprehensive evaluation and monitoring activities with regard to grid connected PV systems were conducted (Erge et al., 2001). In the previous period also such activities had been conducted, however the data was still limited at that time due to the fact that the program was just running. Thus in this period more detailed data could be gathered on the systems installed during the 1000 roofs program. This knowledge also led to learning in practice, which is shown by the decrease in the number of failures over time as can be seen in figure 9.6 (Erge et al., 2001).

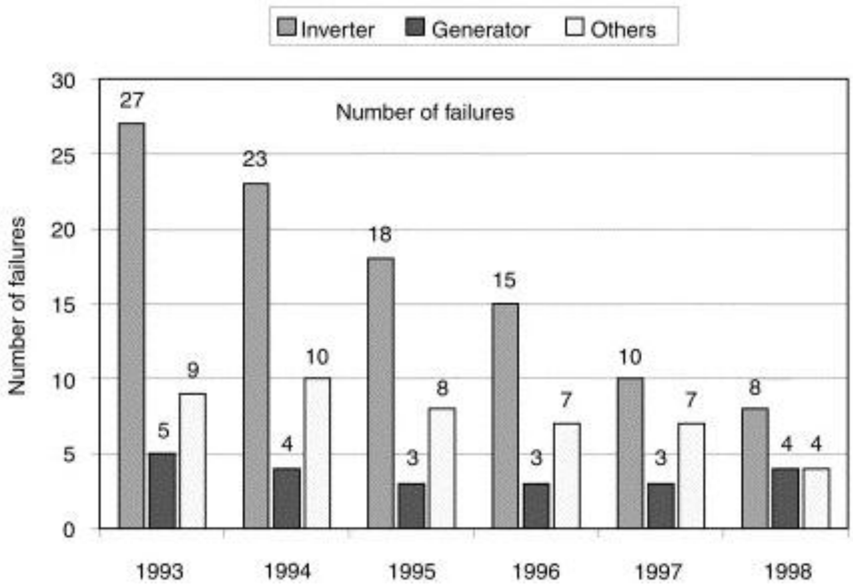


Figure 9.6: Reported failures per 100 systems per component (Erge et al., 2001).

Nonetheless, for some system owners the user satisfaction was damaged due to things such as bad service (e.g. long waiting times), which surfaced the need to improve not only to learn from technical issue, but also from non-technical issues (Erge et al., 2001).

Supporting technologies

In invertor technology developments had taken place that were important to grid-connected systems; Reliability of inverters continued steadily to increase and was better than at the time of the 1000 roofs program and before (Bruns et al., 2011). Furthermore, when the 1000 roofs program was assessed it turned out that replacement of the inverter in older systems was necessary every 8 to 10 years in older to minimize downtime of the system (Bruns et al., 2011).

9.3 Knowledge diffusion

Silicon

In this period the University of Konstanz, one of the main contributors to c-Si research in this period, was cooperating with Bayer AG on the topic of Ribbon Growth on Substrate (RGS). The efficiencies of solar cells produced in this way were still significantly lower than c-Si cells produced through other methods, and the cooperation between the two parties was aimed at getting higher efficiencies through this period, see for example Spiegel et al., (1998). The main advantage of the RGS process is the lower material costs of the silicon, as the silicon wafer makes up a significant part of the total costs. Also the University of Konstanz cooperated with foreign institutes, such as institutes from the USA and Switzerland. One such cooperation focuses on a comparison of several c-Si surface passivation techniques (necessary to increase total efficiency of the cell) (Keppner et al., 1994). It is therefore likely that this cooperation was started in order to combine expertise on these different techniques and bring out a joint paper for comparison.

Also the University of Stuttgart cooperated in the field of c-Si, for example with the Max Plank institute and an institute from the UK on an applied research topic (c-Si films on a novel high temperature glass for new applications) (Bergmann et al., 1998).

International cooperation furthermore took place for example by the Institute for Solar energy research, e.g. in a basic research paper involving two institutes from Australia (Altermatt et al., 1997).

Siemens cooperated in the field of c-Si with Swiss institutes, e.g. see Meier et al., (1997).

Thin film

Interesting here to mention is the international collaboration of SSI as part of the Thin-Film Photovoltaics Partnership Program, which has as it goal *"to elucidate the critical R&D issues and help U.S. industry solve problems prior to market entry"*. Key players in the world were identified for this in the area of CIS and CdTe thin-film technologies. (Ullal et al., 1997).

In the area of CIS, cooperation took place between IPE and ZSW on the up scaling and large scale in-line production. This cooperation can be called vertical cooperation, as IPE and ZSW were active in different parts of the value chain (Wirtz & Janssen, 2010). IPE was active in the field of fundamental research and development on laboratory scale, whereas ZSW was focused on research oriented towards application with their know-how in production technology and the further development towards pilot plant scale (Wirtz & Jansen, 2010). The cooperation was characterized by the exchange of knowledge which led to a gain of knowledge on both sides, with the aim of developing CIS production of to the stage of pilot plant scale. This was done with the purpose of raising interest for the CIS technology from industry and to show the economic potential (Wirtz & Janssen, 2010). Apparently this was a successful effort, as the Würth Group later on in 2006 picked up the mass production of CIS modules and became a successful company. In 1995, there was a project called EuroCIS (a network that coordinates joint efforts in R&D on CIS). Within the scope of this project, a small module (100cm^2) with an efficiency of over 10% was developed successfully and thus IPE and ZSW had proven that large-scale production carried significant economic potential (Wirtz & Janssen, 2010). In order to move to pilot plant scale, the IPE and ZSW had to find a partner which they found in PST (Phototronics Solartechnik). The cooperation succeeded in 1997 in the pilot plant scale development of CIS modules, however due to a change in strategy PST left the cooperation after this success (Wirtz & Janssen, 2010).

9.4 Guidance of search

In this phase, it seems that the government did not consider grid-connected PV systems as a viable option. The 100,000 roofs program was rejected by the government, and the Federal Research Minister at the time (Jürgen Rütggers) did not see much in funding photovoltaics (Bruns et al., 2011). He believed that there was little potential for electricity generation costs of PV to go below 50 cents/kWh and thus he was not in favor of state subsidies for PV (Bruns et al., 2011). Although he was opposed to funding grid-connected systems, he did propose systems that operated independently of the grid, and viewed hand-held devices and small-scale systems as having the greatest potential for the application of PV. For that reason this area of application was given priority in the funding within the Fourth Energy Research and Technology Program (Bruns et al., 2011). Furthermore, from the government there were plans to stop the funding of research for PV power plants by the end of the period, although this field of application received large amounts of funding since the 80'ies (Bruns et al., 2011). However, some funding remained, due to the fact that the government allocated interest earning from the auction of UMTS licenses (for the use of the spectrum), which were sold in the year 2000. This helped to continue the research into PV power plants in Germany (Bruns et al., 2011). The development of public funding for RD&D on PV is shown in figure 9.7.

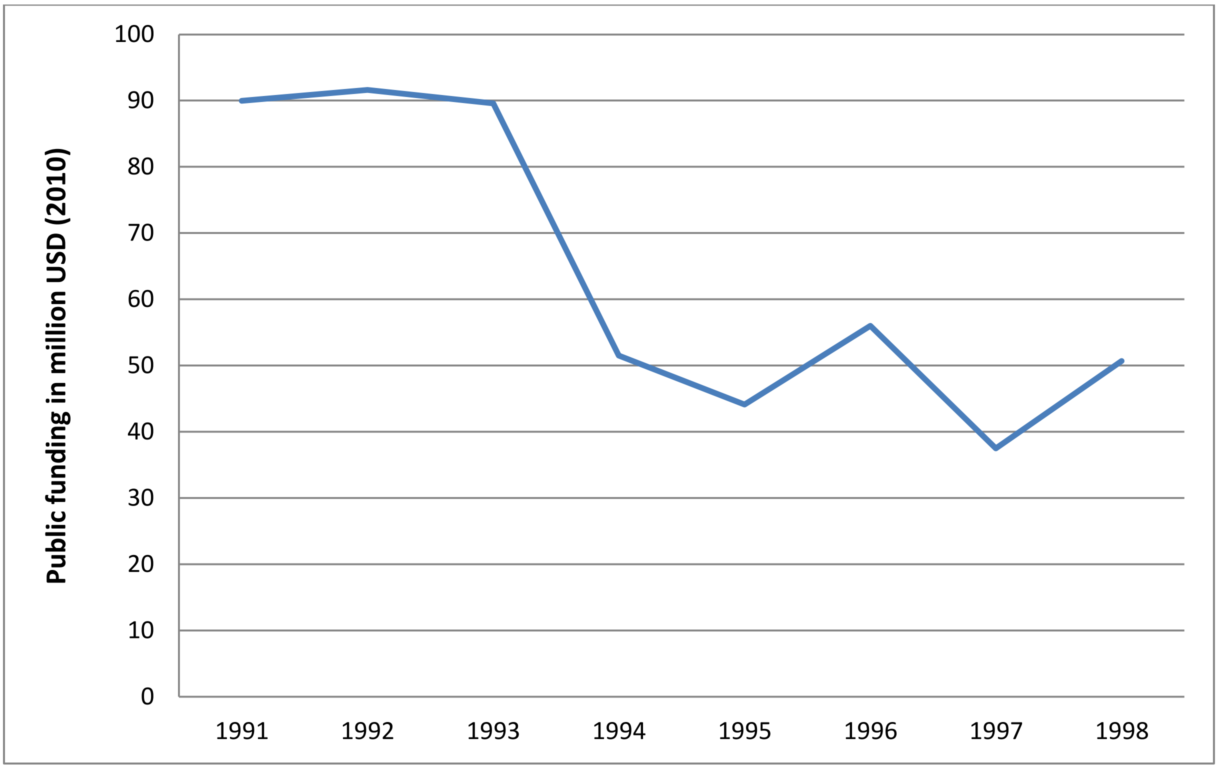


Figure 9.7: Development of public RD&D funding for PV in the period 1991-1998 in Million USD (2010 prices and exchange rates) (IEA Database, 2012).

From the figure it can be seen that the RD&D funding in this period experienced a drop in 1994 and fluctuated for the rest of the period. However, as mentioned in section 9.2.1 the amount of research papers in general on PV technologies increased, albeit in a fluctuating manner.

In figure 9.8 the development of governmental R&D funding is shown together with the development of the number of papers on solar cells.

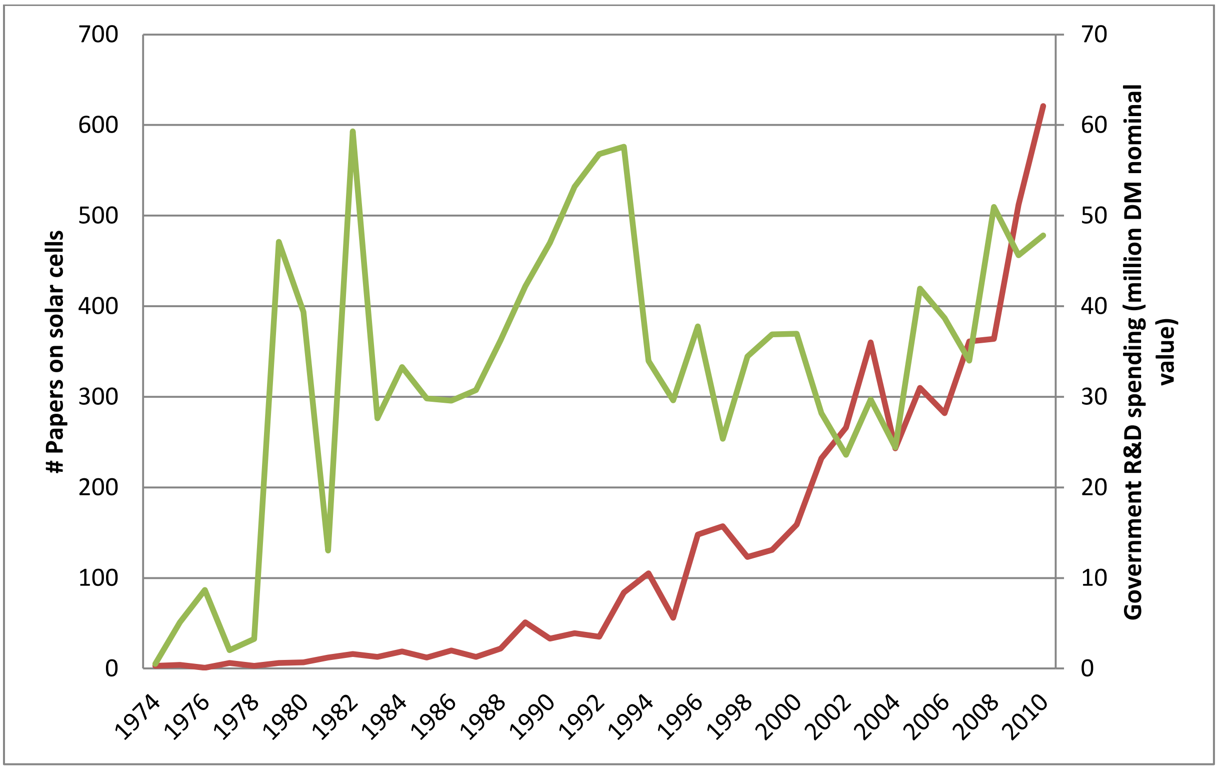


Figure 9.8: Development of the number of papers on solar cells from German origin together with the development of governmental R&D funding

It can be seen that the R&D in this period was very much fluctuating after experiencing a steep drop in the previous period. This is reflected in the number of papers appearing on solar cells in this period, although overall the number of papers on PV was rising, which cannot be said for the governmental R&D funding in this period. This indicates that the "guidance of search" function was fulfilled by more than just governmental funding.

9.5 Market formation

While in Germany the market was going through a phase of weak and fluctuating growth, the international market developed independently and showed more growth (Bruns et al., 2011). The 100,000 roofs program, which was to have a great impact on the sector, did not start until the next phase, a draft bill was introduced by the SPD (the party of Hermann Scheer from Eurosolar) for the 100,000 roofs program in 1996 (Bruns et al., 2011). The aim of this program was to support the shift of PV to the stage of mass production, and it supplied investment grants for small-scale private users. In contrast to private users, Energy supply companies were not included in the program. The draft was furthermore rejected by the CDU/CSU/FDP government and did not pass (Bruns et al., 2011). The government furthermore had no coherent strategy for the expansion of the PV sector at this time. As the Federal Research Ministry promoted PV in the previous phase (for example through the 1000 roofs program, the Federal Ministry of Economics failed to facilitate the market introduction of PV. It did not do absolutely nothing (e.g. it introduced the StrEG for compensation rates), however these measures were too small to facilitate positive conditions for the manufacturing of PV in Germany (Bruns et al., 2011). For example, the StrEG compensated only about a tenth of the incurred costs (Bruns et al., 2011). Thus, the PV sector criticized the absence of a real market introduction program, which was needed in order to withstand competition from the USA; from each five systems manufactured in the USA, one would be exported to Germany in this period, which, considering the difficult situation in Germany (too little funding and compensation rates), brought German companies in a difficult position (Bruns et al., 2011).

But, just as the entrepreneurial activities did not stop, the support for PV did not stop entirely either. Although funding from the federal level was lacking, there were a number of regional initiatives that helped the PV sector to continue development, initiated by local governments in order to compensate the low funding from the federal level, and even by some public utilities (Bruns et al., 2011). The experience gained from the 1000 roofs program in the previous period was the basis for the programs of other sponsors. An example of this is the REN program, which was discussed earlier, and also applied in this period (and beyond) (Bruns et al., 2011). Furthermore, some municipalities had introduced cost-covering payments in 1993, and this continued in this period. This has enabled the further construction of PV systems,; more than 10 MW was installed by the end of 1999 and thus these local municipal initiatives helped to continue the development of the PV sector, even though the 1000 roofs program had ended (Bruns et al., 2011). This development is shown in table 9.4.

	1990	1991	1992	1993	1994	1995	1996	1997	1998
Installed capacity (MWp)	1	2	3	5	6	8	11	18	23
New installations (MWp)		1	1	2	1	2	3	7	5
Growth on previous year		100%	50%	67%	20%	33%	38%	64%	28%
Market stimulated by:		1,000 Roofs Program				Municipal cost-covering compensation			

Table 9.4: Installed PV capacity 1990 to 1998 in Germany (Bruns et al., 2011).

The concept of cost-covering payment was new; instead of providing compensation for the costs of the system, it provided remuneration for PV generated electricity fed intro the (public) grid by utilities, and solar system operators were completely compensated for their costs during a guaranteed period of 20 years (Bruns et al., 2011). The grid operator makes the payment to the supplying plant operator. The rate of remuneration per kWh was based on the price of an optimized system that was produced in the same year, varied between municipalities and was financed by an increase in the electricity price (Bruns et al., 2011). The Association for the Promotion of Solar Energy (SFV) had already proposed this measure in 1989 as a market introduction tool for PV systems and was of vital importance to get this act through(SFV, 2001). When the cost covering payment was first implemented in Aachen, it met considerable resistance by a municipal utility (STAWAG), however in 1995 the first contract between a producer of solar energy (i.e. the one that feeds the electricity into the grid) and STAWAG was finalized and within the coming years tens of cities adopted the cost covering payment, such as Bonn and Nuremberg (Bruns et al., 2011). The cost covering payment would later on be the basis for a considerable part of the famous Renewable Energies Act (EEG) (Bruns et al., 2011).

Many municipal energy suppliers did not provide compensation that covered all the costs, although they did increase the rate of compensation. Nonetheless, in general the municipal utilities that worked closely together with large utilities, or in which large utilities were major stakeholders, turned down requests for a compensation that was cost covering, or increases in compensation, even though they incurred no additional expensed due to the increase of the general electricity prices (Bruns et al., 2011). The apportionment of costs was overseen by the German states, and helped to continue the increase in PV systems (Bruns et al., 2011).

Also energy suppliers became active in the field of PV; for example Bayernwerk AG invested in a 50 kW installation and sold shares (20 pfennigs/kWh) to about 100 people, and this led to the formation of other similar models. The 15,000 people that got their energy from renewable sources paid an eco-tariff that was approximately twice the normal price for electricity (Bruns et al., 2011). Another example can be found in RWE (a utility company), that installed 25 PV systems (2 kW capacity per system) in a row housing project in Essen. Although the aim was to learn with regards to installation, integration and operation of the network, this initiative amongst others contributed to the limited growth in this phase (Bruns et al., 2011). Another example is Bayernwerk AG, which funded 544 installation (1 kW capacity) as part of the “Sonne in der Schüle” program. The total installed capacity under the program from 1994 to 1997 was 610 kW, and the program caused students and teachers to get in direct contact with the new theme of solar energy (SEV Bayern, 2011). Also the utility PreussenElektra financed PV systems for rooftops on schools; 450 schools in the North of Germany got a 1 kW PV installation under the “SONNEonline” program. The program had a parallel measuring program which was coordinated by the Fraunhofer Institute in Freiburg (SEV Bayern, 2011). Although the market growth was weak, the number of municipalities providing local feed-in tariffs and the initiatives of some utilities revealed a broad interest in PV (Bruns et al., 2011). It can furthermore be said, that although uncertainty existed for the PV sector due to the ending of the 1000 roofs program, the demand did not fall and was even higher than under the 1000 roofs program, as annually 4 to 12 MW of systems was installed from 1995 to 1998 (Bruns et al., 2011).

However, by the end of the period in 1998 the PV sector went through a difficult phase; while before that time the prices of PV systems decreased, in 1998 the price of a 1kW system stagnated at about 8000 euro (Bruns et al., 2011). Furthermore, the demand in 1998 experienced a drop of 25% compared to the previous year for the first time; often this is attributed due to ineffective funding policy, which was often very complicated to get your way through, as well as the stagnating or decreasing municipal support (Bruns et al., 2011). Also, some parties waited before investing due to the hope that the coming elections would bring more favorable conditions for PV investments (Erge et al., 2001). The demand that *was* present can be explained through the pioneering attitude of the initial users of PV that did not have profit as their main concern. Instead, they invested in PV due to environmental or moral principles, but the prospect of coming policies and programs gave them an extra boost to put this into action (Bruns et al., 2011). PV was an excellent option for such private investors, due to the fact that a PV system is modular in nature and can be applied in small scale systems, and thus suitable for individual households (Bruns et al., 2011).

9.6 Resources mobilization

In this period there appeared to be a shortage of silicon supply, due to the increasing international demand, which led to rising prices difficulties for cell manufacturers (Bruns et al., 2011). The PV industry at the time was tuned towards the semiconductor industry; silicon that did not meet the requirements needed in the semiconductor industry could be used by the PV industry, and thus some time was needed before the supply was increased in order to provide for the growing demand from the PV industry (Bruns et al., 2011).

Although the growth in this period was limited, this is a relative notion as there was a boom of startups at the end of the period, possibly triggered by the prospects offered by the coming 100,000 roofs program (Bruns et al., 2011). However, in order for this boom to happen, something else was needed: Corporate financing. A new phase of corporate financing emerged in this period which is known as the "New Economy" (Bruns et al., 2011). In the period 1975-1995, the growth rate of output/hour was on average about one percent a year, however from 1995-1999 this growth became 2.65% and thus grew considerably(Gordon R.J ;2000). Different trends in this New Economy have been identified, such as the spread in capitalism over the world and the information revolution (Shepard, 1997). In this development investors were willing to invest large amounts of money as venture capital for startups which were often in the form of stock corporations collecting capital; shares were subsequently traded on the "Neuer Markt" at Frankfurt stock exchange (Bruns et al., 2011). The Neuer Markt was a special segment of the Frankfurt stock exchange, launched in 1997 with the goal of equaling the NASDAQ as a stock market for innovating startups. Nonetheless, the Neuer Markt closed some years later due to losing much of its value or regulatory changes (Cave, 2002). Many companies collapsed in 2000/2001, perhaps partly due to an over-optimistic attitude that led investors to not pay attention on where exactly the capital would be invested; after this it became extremely difficult for startups to get capital from the stock market (Bruns et al., 2011). An example of such a company emerging from the "Neuer Market" is probably SolarWorld, as it was the first PV energy company to go public and was listed on the stock market in 1997/1998 as mentioned earlier, which implies that they (successfully) raised capital through the stock market.

9.7 Advocacy coalitions

In this period, other local initiatives followed in some cities as the result of the growing support for solar energies. These smaller contributions were essential in initiating a "public wave of support" for solar energy, and it was key to the survival of the (at that time) small PV industry (Palz, 2010a). For example, the Association for the Promotion of Solar Energy in Aachen was important in this regard as it promoted the concept of cost covering payment which was implemented in a number of municipalities and helped prevent the downfall of PV, and shape the EEG which proved to be instrumental later on (Bruns et al., 2011).

The ongoing development of PV was met with political resistance, and a reaction was needed through media, legal ways and through politics in the parliament. An example that highlights the need for a reaction through legal ways is that energy companies for years tried to get around the legal provisions of the measures to stimulate PV, and thus many times cases were brought before the court. The prevailing ideas amongst legal scholars and in their literature thus had to be influenced, and this led to the initiation of a law periodical specific for renewable energies: *Zeitschrift für Neues Energierecht*, or Magazine for New Energy Law, which was started by Hermann Scheer from EUROSOLAR and several lawyers and law professors. It appeared ever since and it was vital in moving the legal culture towards a more favorable one for renewable energies (Palz, 2010).

In 1998, the 100,000 program was firmly established in the SPD party program, the party which, together with the Greens, got the majority of votes after the general elections. Thus, they formed the new federal Government (Palz, 2010) . However, this establishment of the 100,000 program in the SPD party program was not without problems, due to a similar effort of Greenpeace which called for a 50,000 roofs program. Hermann Scheer explains: “*So I was asked at the meeting of SPD leaders why the SPD should demand even more than Greenpeace, but I won the day with the argument that we should be thinking of industrial mobilization for such a very big step.”* (Palz, 2010). However, even though the 100,000 roofs program prevailed over the 50,000 roofs program, it was not initially included in the governmental program made by SPD and the Greens and further negotiations were necessary. This proved to be difficult, as the new government budget would only be passed in June 1999, which meant that anyone wishing to purchase a PV system would have to wait for about eight months before the start of the program, implying that in the mean-time no orders for PV system would be made. Thus efforts took place by Herman Scheer to involve the KfW, a state-run development loan corporation, for pre-financing of the program. This was subsequently accepted, the program was drafted together with KfW, the finance ministry and two members of the Green party in parliament. The program was started on 1 January 1999.

9.8 Conclusion

In this phase, no large scale diffusion of PV in Germany yet occurred. For most part of the period there was not much growth and just a few big companies were active in manufacturing PV modules. On the other hand, however, new silicon solar companies were entering more towards the end of the period which is likely linked to the advent of the 100,000 roofs program, which was also facilitated by the “New Economy”. PV companies active in the field of crystalline silicon solar were most likely to benefit from such roof programs, due to the fact that these cells offered the most economic option by far due to their higher efficiency and tested use. R&D in the meantime was fluctuating, but overall increasing, even though the governmental R&D funding showed fluctuation but no increase. Thus this indicates that PV was becoming more and more a relevant topic in and of itself in R&D, not so much because of funding but because of the inherent expectations coming with the technology. The R&D coverage of PV technologies was broad, both in industry and in research institutes. This shows that no single technology was considered as being most likely to dominate in the feature. Nonetheless, the market formation that was slowly initiated on a small scale in the local communities implicitly favored crystalline silicon solar cells, as these programs were focused on an application (i.e. roofs) were c-Si were by far most suitable from an economic and experience perspective. These local initiatives furthermore seemed to have helped to have played a sort of bridging role between the 1000 roofs program that had ended and the 100,000 roofs program that was to come. Furthermore essential steps were undertaken in order to establish the 100,000 roofs program in the following period, although this program had previously been rejected. Thus although the takeoff for PV in Germany did not yet start, it seems that the forces were heaping up and ready for launch, waiting for the right conditions to emerge in the next period.

10. 1999-2003

10.1 Entrepreneurial activities

Productivity of PV firms in general in Germany experienced strong growth in this period. Consider for example the growth from 2002 to 2003, for PV in general: The production was 57 MW in 2002, and 110 in 2003 (Stubenraum. 2003). There was also an expansion of capacity, from 94 MW in 2002 to 135 in 2003. Module production amounted to 82,5 MW (Stubenraum, 2003). Table 10.1 shows the development of module production in Germany over the years.

Table 10.1: Development of PV module production in Germany over the years (Stubenraum, 2003).

	1996	1998	1999	2000	2001	2002	2003
Total Production	3,0	6,4	8,8	16,1	29,0	41	82,5

Furthermore, there had been a growth in labor places and around 12000 labor places existed by the end of 2003 in the German PV sector, showing its growing importance (Stubenraum, 2003).

Silicon

From this time onwards a take-off period can be discerned for the German solar market according to (Jacobsson & Lauber, 2006), which is confirmed by the increasing number of companies that enter the solar market just before or in this period. For example Q Cells, one the largest cell and module manufacturers in the world today started the production of silicon solar cells in 1999, as well as Schott Solar, Sunways and Solarworld. Furthermore in 1999 Crystalox (an equipment producer for industrial production of ingots) entered into a strategic partnership with PV Silicon (PV Crystalox, 2011). Thus the 100,000 roofs program attracted activity, initiated in order to profit from the newly created potential demand for solar electricity. However, the original feed-in law, which was at first not sufficient for a take-off, was about to be revised in favor of renewable energy; After the revision procedure, which started in 1999, the Renewable Energy Resources Act was successfully adopted in 2000 (Jacobbson & Lauber, 2006). This apparently provided enough incentive for further entry of firms: For example, in 2000 Solarwatt started with the series production of silicon modules and in 2001 module manufacturers such as Axitec, Conergy (also manufactures cells) and Aleo and entered the market, and in 2002 the PV Crystalox Group was founded which produced silicon ingots and wafers (PV Crystalox, 2011). Not all companies have survived (at least in their former state): For example AEG and ASE flowed into Schott Solar, and in 2001 Shell Solar took over Siemens Solar (PV-Tech, 2011). In 2000, Shell announced an investment of DM 50 million in a 25MW PV production plant (for polycrystalline modules) in Germany, and Shell had as its goal a 10% global market share by 2005.

The turnover of the PV sector in this phase grew from 200 million to 500 million euros, the number of employees in the sector grew from 2,500 to 6,500 in 2001 and the production capacity grew from 6MW to almost 100MW (Bruns et al., 2011). Furthermore, in 2001 over 250 PV system installation companies and 20 module and component distributors were active domestically and internationally (Erge et al., 2011). An overview of some German companies active in the c-Si field is given in table 10.2.

Table 10.2: Overview of a number of German firms active in the field of c-Si (Stubenraum, 2003).

Cell/Module manufacturer	Technology (sc-Si, mc-Si, a-Si, CdTe)	Total Production (MW)		Maximum production capacity (MW at the end of the year 2002)		Additional Information
		Cell	Module	Cell	Module	
1. Alfasolar Vertriebsgesellschaft mbH			3 (2,5)			
2. Deutsche Cell GmbH, Freiberg		17		30		
3. Ersol Solar Energy GmbH Erfurt	mc-Si	9,0 (9,0)		10,0		Ersol produces solar cells with two production lines. The further extension of the production line and the start of an additional PV module production (mc-Si 160 W) is planned for 2003.
4. Scheuten Solar Technology (former Flabeg Solar International GmbH)	sc-Si mc-Si		2,9 (2,5)	8,0		Specialized in modules (140W–230W) for integration into buildings and façades. In 2001 a new high-tech production line for standard modules with a capacity of 9,0 MW (3 shifts) was installed in Gelsenkirchen and started operation in early 2002. Recently the company became insolvent and closed the production.
5. GSS GmbH and IPEG GmbH, Löbichau	mc-Si		4 (2,5)			Manufactures mainly custom made frameless PV modules (80-290W) for integration into buildings. Acquired in 2000 by Atlantis Energie AG. IPEG is a spin-off company of GSS.
6. Q-Cells AG, Thalheim	mc-Si	28,2 (9,0)		24,0		A new company on the market in 2001. The cell production line has been designed for maximum performance and flexibility: to produce high performance and process both poly- and mono-crystalline materials and to handle formats of 100, 125 or 150 mm cells Start of production in July 2001.
7. RWE Schott Solar GmbH, Alzenau	EFG mc-Si	40 (25)	5 (0,5)	43,0		RWE Schott Solar is a joint venture between RWE Solutions AG and Schott Glas AG. In this company, founded in october 2002, the two companies have bundled all their terrestric photovoltaic activities, like RWE Solar GmbH, the american ASE Americas, Inc and the american SCHOTT Applied Power Corporation. In spring 2003, the first prduction lione of RWE Schott Solar`s SmartSolarFab went into full operation. Until the end of 2004, a capacity of 60 MW solar cells based on the EFG film technology will be realised.
8. Saint Gobain Glass Solar GmbH, Aachen	mc-Si		<1 ?(1,0)			Former Vegla, produces PV modules for integration in buildings (glass-glass, isolating glass).
9. Shell Solar GmbH, Gelsenkirchen	sc-Si mc-Si	9 (9,0)	0 (5,0)	13 (10,0)		Shell Solar is producing mc-Solar cells in Gelsenkirchen. In 2001, Siemens Solar and Shell Solar has merged to a joint venture, the Siemens & Shell Solar GmbH. In early 2002 Shell Solar has taken over all shares of Siemens (34%) and the utility Eon (33%) and the company was renamed in Shell Solar.
10. Solara AG, Hamburg			6 (3,0)			The main distributor of Photowatt in Germany started a production line in Wismar and produced the first modules in 2001. The capacity is planned in several steps up to 24 MW.
11. Solar Fabrik GmbH, Freiburg	sc-Si sc-Si		8,5 (7,2)			Founded in 1993, started PV module production (75W-115W) in 1997 in co-operation with Astropower. Produces modules since 1999 in a new factory designed and built according to ecological regulations.
12. Solar Factory GmbH			7			

Total production and capacity have already been mentioned.

An overview of the development of PV production in MW is given in figure 10.1.

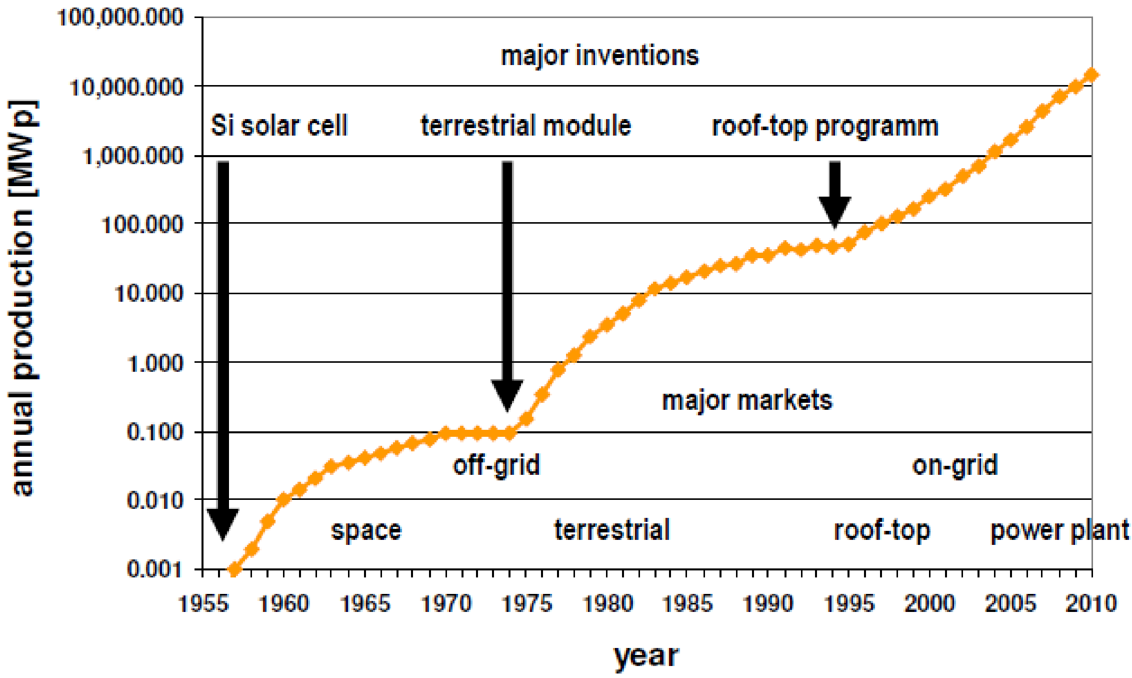


Figure 10.1: Historic development of annual PV production in MW (Breyer et al., 2010)

It can be clearly seen from the previous that the PV market at this time was at a much more mature stage than in the previous period, and growing. Also interesting to see is that by now to large firms were fully integrated companies, showing their desire to become independent of market fluctuations. These companies were Solar World and RWE Schott Solar (Stubenraumer, 2003). Thus

Thin film

In 2002, there was a total PV production of 500 MWp/year, of which over 85% was taken up by crystalline silicon technologies (Diehl et al., 2005). This implies that a minority but significant share of around 10-15% was taken by thin film technologies. Thin film was getting more attractive due to the silicon shortage due to limitations of the silicon feedstock. Nonetheless, at this time only two German companies had production lines, namely Phototronics (PST) division of RWE-Schott Solar with a a-Si production line and Antec Solar Energy GmbH (formerly Antec Solar GmbH) with CdTe technology according to Diehl et al. (2005), however Würth seems also to have had a (pilot) production line in CIS solar cells by 2003 (Stubenraum, 2005) which would bring the total amount to three. Entrepreneurial activities did take place from other companies as they were looking to enter the market. Although the activities of such companies (e.g. Shell Solar, Sulfurcell) were still mainly R&D related, they also had a clear entrepreneurial component in the form of starting up pilot production etc. It appears that most new entrepreneurial activity in the field of thin film cells took place with regard to CIS technology. Table 10.3 gives an overview of the firms with production lines along with their capacity.

Tabel 10.3: Overview of German manufacturers in the thin film sector (Stubenraum, 2003).

Cell/Module manufacturer	Technology (sc-Si, mc-Si, a-Si, CdTe)	Total Production (MW)		Maximum production capacity (MW at the end of the year 2002)		Additional Information
		Cell	Module	Cell	Module	
1. AnTec Solar GmbH, Rudisleben	Cd-Te		5 (1,5)		10,0	Since 1998 installation of a production line in so-called Advanced Thin-Film Technology (ATF). Since September 2001 production in small quantities. Due to insolvency production was temporary closed. AnTec has found a new investor.
2. RWE Schott Solar GmbH PST, Putzbrunn	a-Si		2 (1,0)		3,0	Phototronics is a subsidiary of RWE Schott Solar. Production and R&D of amorphous thin-film cells and modules. Developed modules with a-Si/a-SiGe tandem cell structures.
3. Würth Solar GmbH, Marbach am Neckar	CIS		0,4 (0,15)		0,35	Founded in 1999. Started a small pilot production line for CIS thin-film cells/modules in 2001.
TOTALS			**7,4 (2,65)**			

CIS

The ZSW, that had started development of a large area in line production process for CIS cells, had achieved efficiencies of 12% in 1999. The results of the experimental line and cost studies had generated promising expectations, and the joint venture Würth Solar GmbH & Co KG. was founded between Adolf Würth GmbH & Co KG., Energy Baden-Württemberg (a utilities company) and the ZSW. This joint venture had as its goal the mass production and commercialization of CIS modules and a pilot plant was made. The first modules were made in 2001. (Powalla et al., 2005). The pilot production since then picked up steadily, and production of modules more than doubled every year until a maximum production was reached in 2004 (20,000 modules a year) (Powalla et al., 2005).

Siemens Solar was also active in the field of CIS development, and around the beginning of this period they first brought their CIS modules to the market. In parallel, however, Siemens was conducting R&D on CIS solar cells, most likely in order to upscale the modules. Initially the CIS modules were only suitable for small scale applications (e.g. battery charging) up to 10W, however this was subsequently enhanced to 40W CIS modules which were significant steps towards larger grid connected PV applications (Karg et al., 2001). In 2001, however, Shell Solar was founded in Munich and in 2002/2003 it took over Siemens Solar (Solarworld, 2012). Overall it can be said that CIS solar cells did not yet reach the stage of mass production at this point in time (Powalla & Dimmler, 2003).

There was also a small boom in new startups. In 2000, Solarion GmbH was founded, which did development, production and marketing of CIS thin film cells. In 2001 furthermore Sulfurcell Solartechnik GmbH was founded, although mass production did not start until in the next period (Berlin-Sciences, 2012). Also, in 1999-2000 CIS Solartechnik GmbH was founded, emerging from a leading copper producer (Aurubis) in Europe, due to a related business of this group in producing certain metals that are used also in CIS cells. However until 2005 there would only be laboratory development (CIS-Solartechnik.de, 2012).

a-Si

As mentioned, Phototronics from RWE-Schott Solar was the only firm at this point with a production line. It had a production capacity of 3MWp in 2002 (Diehl et al., 2005).

CdTe

At this point, Antec Solar Energy GmbH had a production capacity of 250 kWp/month in this period with a maximum of 10MWp/year.

10.2 Knowledge development

10.2.1 Learning by searching (R&D)

The development of Germany's R&D budget with regard to PV can be seen in figure 10.2

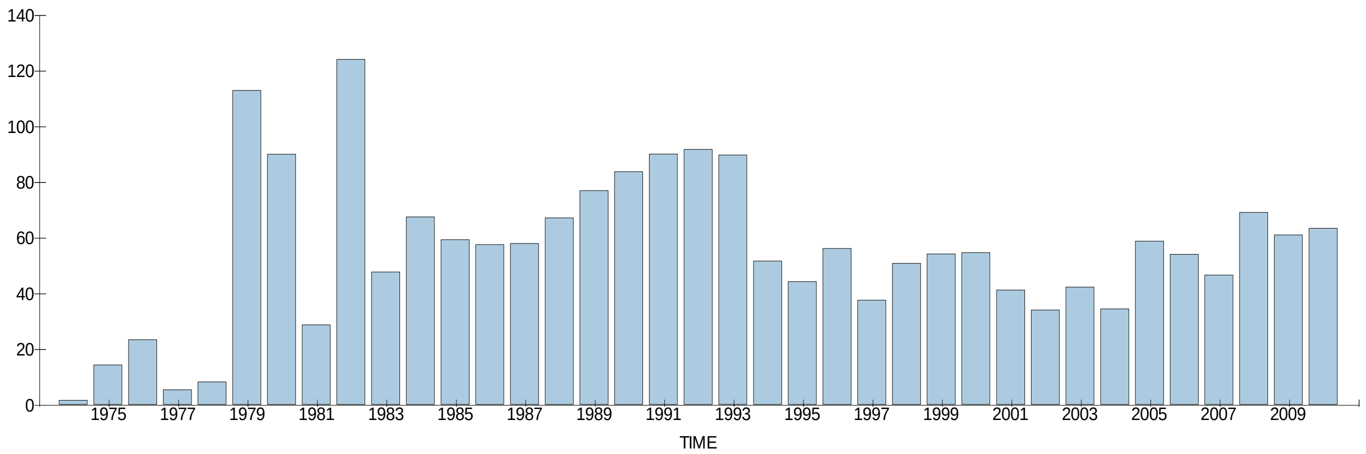


Figure 10.2: Development of R&D budget in million Euro's in Germany with regard to PV (2010 prices and exchange rates)

Thus, funding increased from 2002 to 2003 and amounted to 42,177 M€ (2010 prices, 29,7 M€ 2003 price).

The distribution of funding in 2003 among the different PV technologies can be seen in figure 10.3.

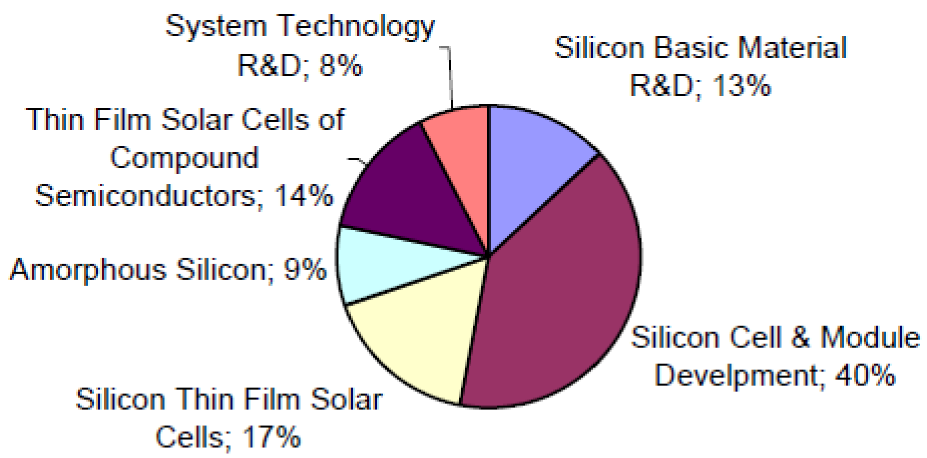
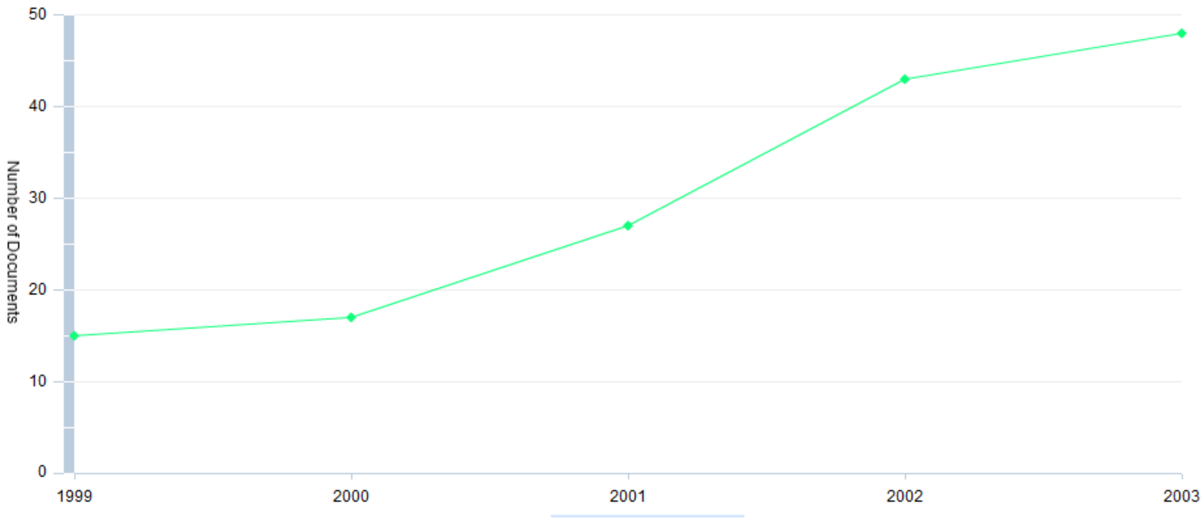


Figure 10.3: Distribution of government R&D funding in 2003 in Germany among different PV technologies (Stubenrauch, 2003).

This shows that the "classic" field of c-Si research was still the biggest receiver of funding.

Silicon

In this period, in contrast to the previous period, a steady increase in the number of German papers on silicon PV can be noticed as shown in figure 10.4.



Figuur 10.4: Development of the number of German papers on crystalline silicon solar cells in the period 1999-2003

Main contributors are again the Fraunhofer Institute, the Jülich research institute and the University of Stuttgart. Also industrial research was being done, for example by Siemens and Shell (Shell would eventually take over Siemens Solar). The research was also funded, as is clear from acknowledgements found in the papers. In this period the importance of materials reduction grew, due to the rising feedstock prices of silicon. Whereas before the wafer costs were about a third of the total costs of a module, in this period this became 50% (Endrös, 2002). Materials reduction can be achieved through a number of ways, such as reducing the cost of the wire sawing process, improving costs of crystal growth, and cutting thinner wafers (Endrös, 2002). Due to the rising costs of raw materials, it is therefore not surprising to see many papers in this period on thin film crystalline silicon from, for example, the Fraunhofer Institute. Thin film c-Si technology underwent great development in these years, however activities will still mainly restricted to research. Also microcrystalline silicon and a-Si:H in combination with c-Si technology (hetero junction cells) seemed to be studied in this period, for example by the Julich research institute and the University of Stuttgart.

The efficiency of cells based on crystalline silicon in this period was experiencing a slow but steady growth, and the cost of modules and systems was slowly reducing (Goetzberger et al., 2003).

Also potential of cost reduction of PV is considered to lie in the increase of efficiency of the silicon solar cells (FVEE, 2003). For example, from the ISFH (a solar R&D institute associated with the university of Hannover) a publication appeared on “Easy-to-fabricate 20% efficient large-area silicon solar cells” **(Metz & Hezel, 2001).** The paper describes an innovative cell structure developed at the institute which can achieve high efficiencies on industry-sized wafers, and the successful upscaling of the manufacturing of this cell on laboratory scale to large-area silicon cells. Another paper from the institute describes the importance of the increase of solar cell efficiency in order for PV to become economic, without using complex technologies **(Hezel, 2002).** In the paper, four simple steps are described in order to produce a particular cell structure developed at the ISFH that can achieve an efficiency of 21%. Furthermore, a custom-made pilot line is described for mass production for 20% efficient Cz (manufactured through the Czochralski method) silicon cells. The paper furthermore seeks to refute the popular idea that higher efficiencies can only be obtained through complex processing, and to demonstrate high efficiency for large-scale commercial solar cells in contrast with merely high efficiency on laboratory scale through an economically and ecologically sound method.

In this period the Fourth Energy Research Program of the federal government was running (1996-2004). Its' main priorities were increasing efficiency rates, improvement of manufacturing and systems technology in order to cut costs, the integration of PV systems into various types of buildings and the transmission of electricity from decentralized energy supply systems that were network independent (Bruns et al., 2011). Also a sub-program within this energy research program existed for PV: Paving the Way for PV 2005 (Wegbereitungsprogramm Photovoltaik 2005) which was implemented from 1996 to 2005. The aim of the program was to take away obstacles that hindered further diffusion of PV, and three key features formed the strategy of the program: Lowering solar cell costs through increasing efficiency and reducing manufacturing costs, using PV to generate network independent and decentralized energy supply, and optimizing the technology and breaking down inhibitions that people might have concerning the integration of PV systems into different kinds of buildings (Bruns et al., 2011).

Thin Film

a-Si

Whereas the number of German papers on crystalline silicon technologies show a steady increase, this is not the case for papers on amorphous silicon thin film technology, as can be seen in figure 10.6.

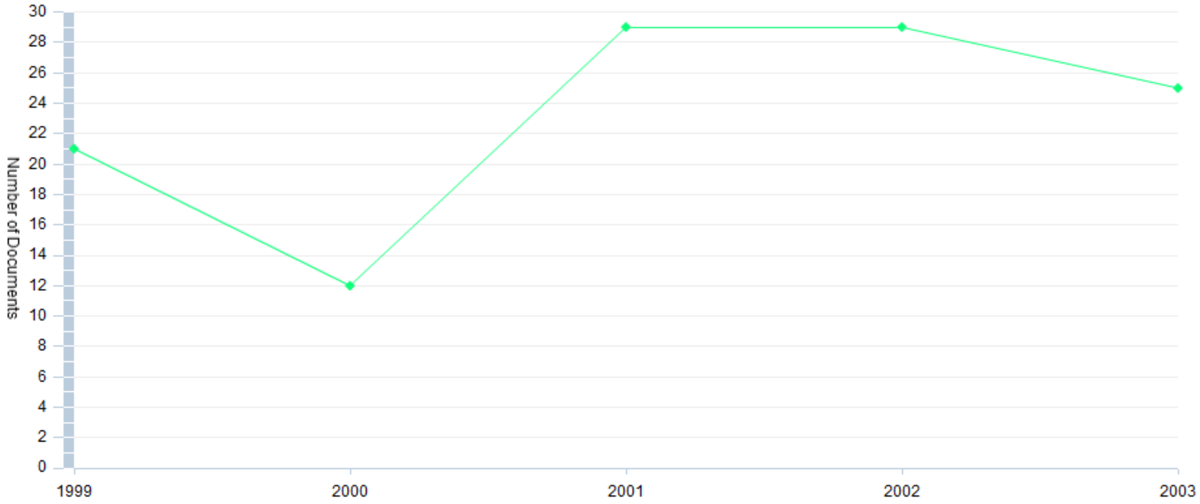


Figure 10.6: Amount of German papers on a-Si thin film technology in the period 1999-2003 from a search on Scopus

A main contributor was the Julich Research Institute, which besides microcrystalline also focused on a-Si cells. The research seems to be of a basic nature, e.g. see Lundszien et al. (2002).

Another main contributor was the University of Stuttgart, of which some of its research seems to be both applied and basic, for example in a paper which describes the impact of deposition temperature on a number of variables (e.g. growth rate and optical band gap)but at the same time also incorporates the material in various solar cell structures to demonstrate the performance of the cells, see Koch et al. (2001).

Also the University of Kaiserslautern was active in the field of a-Si research. The research found was of a basic nature, but with an eye on the eventual application (e.g. scaling up of a deposition process). For example, see Pflüger et al. (2001).

There was little research found from industry on a-Si cells, although RWE Solar/Phototronics was active in the field of a-Si. It was pointed out already in the previous period that Siemens Solar had stopped their a-Si activities (and it was taken over by Shell), and ASE changed to RWE Solar.

CIS

For CIS solar cells, a fluctuating trend can be seen regarding the number of German papers, however different than with a-Si solar, as can be seen in figure 10.7.

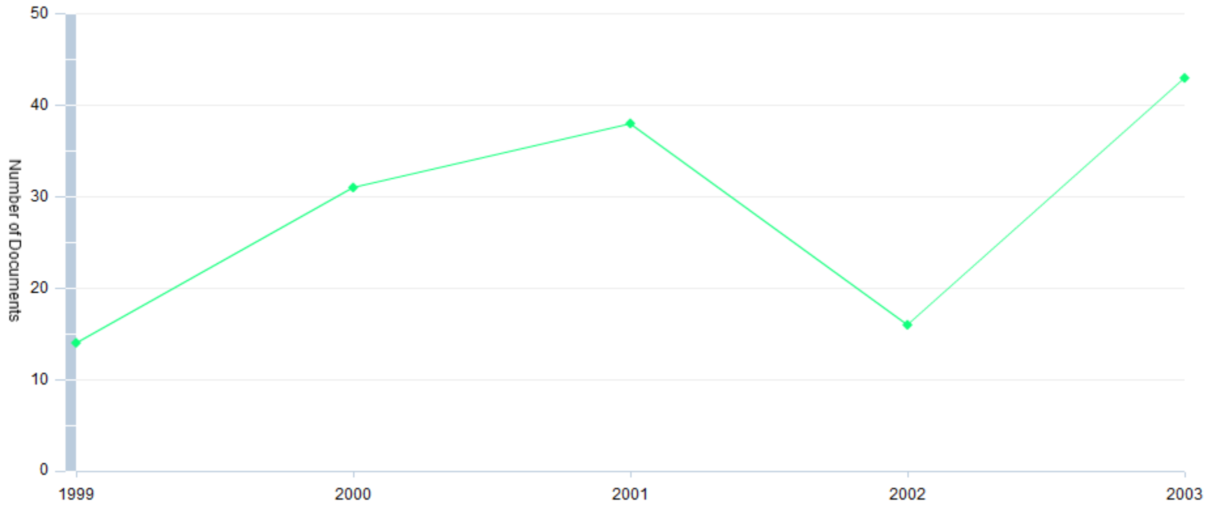
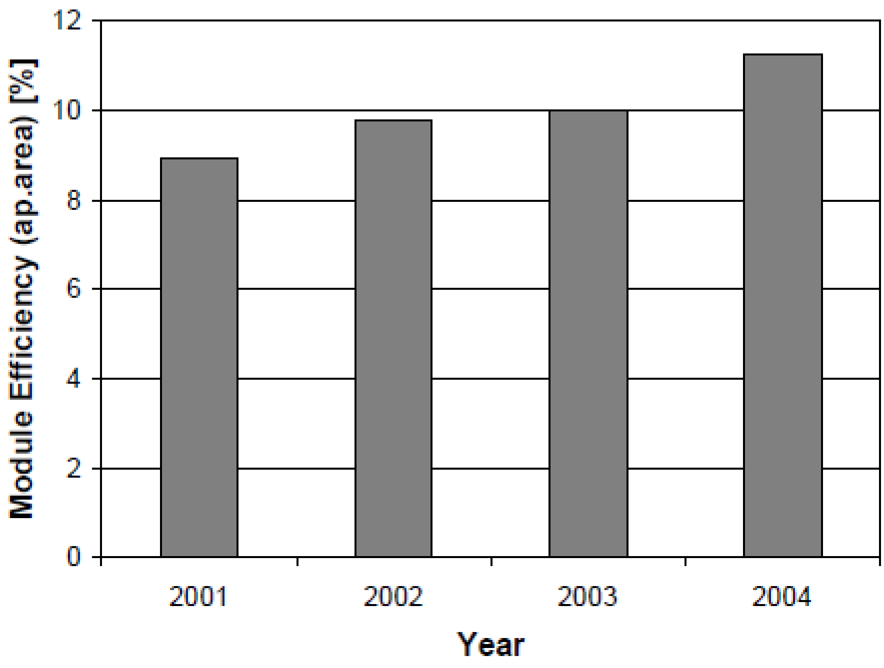


Figure 10.7: Number of German papers on CIS solar cells in the period 1999-2003, taken from Scopus.

An important contributor on CIS research was the Hahn-Meitner Institute. The research of this institute was also of a high level in international context, as is indicated by a top efficiency which was reached in this period (Siemer et al., 2001). The research of this institute was more of an applied nature.

Another main player was the ZSW, of which the research also of an applied nature. This research would prove to be important for the commercialization of the CIS technology, which is indicated by for example a paper from 2003 which describes a productive industrial process technology, which had not been demonstrated up until that point, see for example Powalla & Dimmler (2003). Thus, this German institute was at a very advanced stage of applied research. This research was conducted in cooperation with Wuerth Solar, and builds further on research done by the University of Stuttgart. With regard to module efficiencies, the modules from the pilot line were steadily gaining in efficiency rates. Whereas in 2001 at the start of the pilot line efficiencies were a bit over 8, in 2004 this was already 11,5%, increasing simultaneously with the production (Powalla et al., 2005). In figure 10.8 the development of the efficiencies for the CIS pilot line from Würth Solar is depicted.



Figuur 10.8: Development of efficiencies at the Würth Solar pilot plant (Powalla et al., 2005)

In this period research on CIS was also done by CIS Solartechnik, although this is not commercialized yet even at present. CIS Solartechnik started around 1999 with research, and was busy with testing laboratory scale concepts and developing flexible CIS solar cells cost-effectively in 2000 (CIS-Solartechnik, 2012).

CIS research at this time received funding from the BMWi and BMBF ministries, as well as the European Commission.

10.2.2 Learning by doing

Silicon

In this period, the period where the 100,000 roofs program started, the cost of PV systems went down by 25%, which confirmed the learning curve perspective on PV that costs would go down by 20% with a doubling of installed capacity (FVEE, 2007). As a result of the high demand coming from the 100,000 roofs program, automation of more and more production steps resulted, which was the main reason for the decrease in manufacturing costs, which subsequently led solar module prices to fall as well as system prices (Bruns et al., 2011). Technological advancements were made in each part of the value chain and were accompanied by reductions in cost from silicon production to inverters and installation (Bruns et al., 2011). It also became necessary to adapt processes that had been fine tuned in laboratories for use in industrial production (Bruns et al., 2011). Reductions in price were significant during the period of the 100,000 program, as a small system (up to 4 kW) in 1999 at the beginning of the program cost 7,300 euro/kW, whereas in 2003 at the end of the program the price was 5,500 euro/kW (Bruns et al., 2011). For larger installations, the cost had dropped by 500 euro/kW. The development of costs for small systems can be seen in table 10.4.

Year	Number	kWp	Mean system size (kWp)	Cost of system
1999	70	247	3.53	7,262
2000	150	507	3.38	6,817
2001	396	1,322	3.34	6,865
2002	427	1,448	3.39	6,416
2003	274	947	3.46	5,530

Table 10.4: Overview of cost development for small systems (3-4 kW) in euro/kW (Bruns et al., 2011)

The result of this drop in costs was that the cost per kWh generated by PV was 50-60 euro cents at the end of the program, whereas in the beginning of the 90'ies it had been 1 euro (Bruns et al., 2011). Furthermore, the investment costs for this scale of systems had dropped 50% on average from the early 90'ies to 2003. In the 90'ies, however, not all modules were manufactured in Germany and the module cost was three quarters of the total investment. Also, the leading PV countries at that time were the US and Japan. Thus the potential of lower costs should not be seen exclusively in relation to Germany, but rather in the context of a growing international demand (Bruns et al., 2011).

Thin film

CIS

With regard to low cost production, the most important parameters here are yield and throughput (Powalla et al., 2005). The yield is defined as the percentage of glass panes that are successfully made into a solar module that is up to standards, and it includes all steps in the production process (i.e. from glass palte to module) (Powalla et al., 2005). Figure 10.8 shows the development of the yield at Würth Solar (which produces CIS modules) from 2001 to 2005, and a clear positive development can be seen that indicates learning by doing. In the beginning of 2004, the efficiency required for modules to be up to standard was raised from 8% to 10%, reflecting the increase in efficiencies in the sector (Powalla et al., 2005).

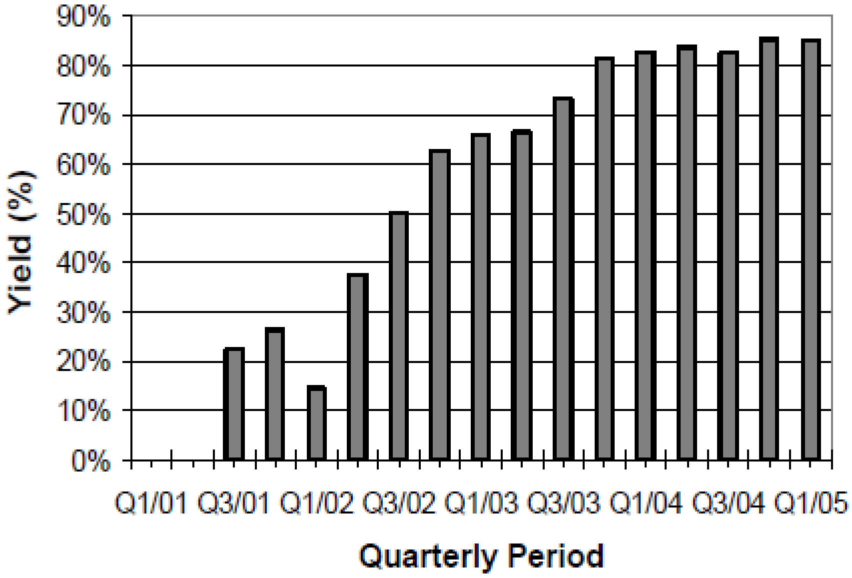


Figure 10.8 Development of yield at Würth Solar from 2001-2005 (Powalla et al., 2005).

Also, from activities at the pilot plant it became clear that one of the biggest obstacles to low-cost production of CIS modules was the cycle time for CIS films. In response to this. Würth Solar decided to double the deposition width from 60 cm to 120 cm, which meant that the throughput was doubled. The first results of production carried out in this way were positive and encouraging to continue. The stability of the process was demonstrated, but also points for improvement surfaced, such as making the quality of the modules more uniform (i.e. narrowing the distribution) and enhancing efficiencies (Powalla et al., 2005).

Supporting technologies

The 100,000 roofs program also had effect on the prices of supporting aspects, such as inverters, other components and installation. In fact, the cost of component was reduced disproportionally compared to the cost modules: During the 100,000 roofs program, the costs of components decreased by more than 50%, whereas the cost of modules decreased “only” 20%, and the price of inverters went from 0,83 to 0,53 cents/W (Bruns et al., 2011). The costs for a system up to 10 kW by component in euro/kW during the 100,000 roofs program are shown in table 10.5.

Year	Number	kWp	Mean system size (kWp)	Generators	Inverters	Installation	Other components	Total
1999	102	312	3.1	4,758	831	693	602	6,884
2000	147	553	3.8	4,499	641	484	509	6,133
2001	514	2,181	4.2	4,939	630	474	479	6,522
2002	752	3,695	4.9	4,413	564	373	429	5,779
2003	289	1,660	5.7	3,861	527	303	330	5,021

Table 10.5: Costs in euro/kW for a system up to 10kW by component during the 100,000 roofs program (Bruns et al., 2011).

10.2.3 Learning by using

In this period, further learning by using took place resulting from the 1000 roofs program which was already discussed earlier on. Also learning by using took place from other programs that had been introduced after the 1000 roofs program but before the 100,000 roofs program, such as the SONNEonline program which consisted of 450 1kW systems for school rooftops being financed by a utility. Twelve systems were equipped with a monitoring system that was intensified and the first measurements on this program were done in 1998 on a total of 25 systems (Erge et al., 2001). While the intensified monitoring program described earlier accompanying the 1000 roofs program revealed performance ratios (a measure for efficiency of conversion of irradiated solar energy) between 55-80% with half of the systems being under 70%, results from the SONNEonline measurement program showed that almost all systems were above 70% with regard to performance ratio. This in part is attributed to increased awareness of installers on high quality demands following the 1000 roofs program (Erge et al., 2011).

Thin film

With regard to CIS cells, an example of learning by using in this phase can be found in Würth Solar and ZSW, which conducted outdoor testing of solar modules at a ZSW test center, in order to check the stability and so called “real-life performance” of the modules (Powalla et al., 2005). The power output of the CIS modules was measured over two years at certain conditions (Powalla et al., 2005). What can be mentioned here is that the testing of the CIS modules from the pilot plant also took place. Whether or not this contributed to learning by using could not be identified, but at least it is a potential way due to the feedback that results after testing (Powalla et al., 2005).

10.3 Knowledge diffusion

Silicon

In this period, the FVS had workshops on crystalline silicon technologies, although considerable less than for thin-film technologies. For example, in 2003 a 287 page document appeared discussing sharing the progress on materials research and process technologies with regard to crystalline wafer technology (FVEE, 2003). The main aim of the research is to reduce the costs of PV technology.

With regard to institutions, one of the leading contributors at this time, the Fraunhofer Institute, was collaborating with the Institute for Solar Research Hameln (ISFH), for example on the topic of optimization of c-Si thin films, e.g. see Kieliba et al. (2003). The Fraunhofer institute also had international collaboration with institutes from the US and China, for example on the characterization of crystalline silicon thin film cells, see Liang et al. (2003). These are not all examples of cooperation from the Fraunhofer Institute, however interesting to mention is the internal collaboration which took place between different departments from the Fraunhofer Institute. The Fraunhofer Institute is a research institute with a broad range of research topics, in fact Europe largest application oriented research organization in Europe today. This allows for expertise from different departments to be combined, which is an advantage that institutions like the Fraunhofer Institute can use, e.g. see Kieliba et al. (2002).

Also the Julich Research Institute collaborated in the field of c-Si technology, although also here a classification problem might arise as to where to categorize the research. This is because the fact that the research done at this institute mainly describes a combination of microcrystalline silicon cells and amorphous silicon tandem cell technology. The Institute cooperated internationally with institutes from for example the Czech Republic and Switzerland on the topic of optical losses and light trapping, e.g. see Vanecek et al. (2003). Again, just like with the Fraunhofer Institute, also internal collaboration between different departments was possible due to the fact that the Julich Institute is als a large interdisciplinary research organization (also one of the largest). For example, one research paper shows that three different departments of the institute collaborated, together with the Walter Schottky institute from the University of Munchen, see Klein et al. (2003).

There was also cooperation between industry and research institutions, for example by RWE Schott Solar GmbH, Ersol Solar Energy AG and the Institute for Solar Energy Research in Hameln (ISFH), on the topic of rear surface passivation for >20% silicon solar cells, as well as between RWE and other research institutes, for an example see Dauwe et al. (2003).

Also international collaboration took place with regard to German industry, for example by Bayer AG with a host of foreign research institutes, for example from France and Belgium, e.g. see De Wolf et al. (2002), as well as with ASE (Americas). Bayer AG also collaborated with the Fraunhofer Institute on crystalline silicon thin film.

This shows that German research and industry could profit from a broad range of national and international research activities.

Thin film

An example of knowledge diffusion that took place in this period can be found in the activities of FVS, the Solar Energy Research Association, which is a cooperative structure of German research institutes active in renewable energies. In 2000, a workshop on deposition of TCO layers was organized (TCO layers function as a transparent window through which the light reaches the active material and as a conducting layer for carrier transport) (FVEE, 2001) . Such a TCO layer is used for generally all thin film solar cells as a front contact (FVEE, 2004). There are different methods of deposition this layer, such as magnetron sputtering and roll to roll processing which were both discussed during the workshop. Also non German researchers were present, for example Dutch researchers from Akzo Nobel Central Research, Arnhem. Basically, in the workshop a short overview and the results of the different processes by the researchers are given. A search through the topics of the workshops shows that the focus of the association with regard to PV lies on thin-film technologies. More specifically, the focus in this period seems to be on deposition techniques for the TCO layers (FVEE, 2011).

In this period not so many firms were active in the area of thin-film cells in Germany. An example of such research and collaboration on TCO can be found in Phototronics from Schott Solar which collaborated with research institutes such as IPV in the FZ Jülich or Fraunhofer IST. It did this primarily in order to reach higher efficiencies (Diehl et al., 2005). In the collaboration project new TCOs were developed as the front contact for a-Si modules and tandem modules with microcrystalline silicon (Diehl et al., 2005). Even though detailed information on this collaboration was not found, it can be assumed that the research institutes focused on achieving high efficiencies from a laboratory perspective, whereas Phototronics as a commercial firm would subsequently be industrializing this technology for commercial production.

With regard to CdTe, Antec Solar Energy GmbH was active in this field. The only supporting research that took place came from the University of Darmstadt. The research focused on interface behavior of the different materials present in the solar cell stack (Diehl et al., 2005).

With regard to CIS, CIS Solartechnik around 1999-2000 prepared a project draft in collaboration with the Institute for Solar Research (ISFH) (CIS-Solartechnik, 2012). The cooperation continued and revolved around a number of topics, such as replacing the relatively expensive vacuum manufacturing process.

10.4 Guidance of search

In 2001 there appeared a EU Directive that promoted electricity generated from renewable energy sources. It's most important aim was to raise the gross electricity consumption in the EU from renewables from 19.7% on average in 1997 to about 22% in 2010. This influenced the development of PV in Germany in the sense that it stabilized the legal framework in an international context (Bruns et al., 2011). Further guidance came from expectations generated by projects abroad. For example, in Japan there was the 70,000 roofs program which was implemented since 1994 in order to introduce PV to the market. The program was long-term and very successful and it served as an inspiration for the 100,000 roofs program (Bruns et al., 2011).

Furthermore, in 2000 the Red-Green coalition government reached an agreement with utilities to decommission all nuclear power plants in the country around 2021-2025 (Petrole et Techniques, 2000). This was a heavy move, as nuclear power accounted for over 30% of power generation in Germany. Not only was this related to a shutdown of existing nuclear plants, but also a ban on the construction of new plants. This implied that the search for alternative energy sources was pushed towards renewables, including PV (Petrole et Techniques, 2000).

Also the local states fulfilled a guiding function. For example, in Lower Saxony the Solar Offensive project was launched 1999 which allocated 20 million DM. The local minister of economics, Wolfgang Jüttner stated that it was the state's aim to drive key technological developments in PV with this campaign and to open up the market for the use of PV (IWR, 2011).

In 2005, the R&D budget saw an increase as can be seen in figure 21. According to Vasseur & Kemp (2011), this was due to an R&D roadmap which was devised in the 9th BMU R&D strategy meeting, which includes people from research institutes and industry.

Berlin, as a member of the Climate Alliance of European Cities, was committed to a reduction of CO2 emissions of 25% by 2010 from 1990 as the base year. In order to reach this, several milestones have been reached over the years, amongst which is the Berlin Solar Campaign launched by the Berlin Senator which was effective from 2000 to 2002. One of the goals of this program was to enhance the public awareness with regard to PV, in order to boost the investment in PV installations. The raising of awareness was targeted through the setting up of a Solar Service Center (provides expert advice on technical issues, grant programs and brokers contracts), the Solar Info Mobile (provides information on PV in pedestrian zones and in front of shopping malls about 20 times a year) and targeted information and activities in press (including a free brochure with information on solar energy, a solar festival and prize draws). Also the installing of PV systems was encouraged for example by crowning the contractor that installs most PV systems as the "solar king". Furthermore training was facilitated as well as exchange of experience, through the Berlin Solar School, the

SolarEnergy trade fair, lectures, courses, seminars and (international) conferences (Energie Cités, 2001).

Expectations

Expectations with regard to PV in Germany had been growing as a result of the new policy initiatives, as is exemplified by the new entrants (see the function of entrepreneurial activities). For example, Shell expected the global market to reach a size of $5 billion by 2010 (compared to $1 billion at the time in 2000) (Info Chimie Magazine, 2000). Another example is an estimate of the German Association of Solar Energy (DFS), which estimated in 2000 that the amount of installations would increase ten-fold up to 2005 (Brennstoff-Warme-Kraft, 2000).

Silicon

Indirectly, it can be said that the 100,000 roofs program in this period guided the search towards crystalline silicon technologies. Although within the scope of this thesis this connection is difficult to establish in a factual sense, this assertion is supported by the fact that the number of papers on crystalline silicon (thin film) technology showed a steady increase in this period, unlike the number of papers from other (thin film) PV technologies. This is not surprising, due to the fact that the 100,000 roofs program was suited best for c-Si solar cells, or rather c-Si were best suited for the 100,000 program, therefore opening up the market for c-Si cells further and making it more practically relevant.

A more direct for of guidance of search can be found in a roadmap published this period by one of the most relevant research institutions on PV this period, and even today, the Fraunhofer Institute. The roadmap sets out specific targets and milestones for the crystalline silicon technology. Coming from such an institute, with in this period a 20 year background in the field, such a roadmap is bound to have impact in the sector. Scenarios are discussed with regard to the share of the (silicon) feedstock costs in the total amount of costs, which was gaining relevance due to the rising prices as a consequence of the silicon shortage, and goals were formulated as well as a strategy of how to achieve these goals. Examples of goals are 20% efficient solar cells on a large area (15cm^2 x 15cm^2), thin wafers cut through wire sawing, and ultra thin wafers cut through novel techniques, as well as some other goals (Willeke, 2002).

From the roadmap example of the Fraunhofer Institute it can also be seen that a certain issue was at the root of part of the guidance of the search described in the roadmap, namely the silicon shortage. This shortage motivated ever thinner wafers, and higher efficiencies. Of course this was not the only driving force, as PV technology was still not economical without significant financial supporting measures and thus needed cost reductions anyhow. However, the shortage of silicon can be seen as a catalyzer in putting extra pressure to make thinner wafers.

Thin film

At this point (and beyond) there were multiple scenario's that could be envisioned for the future, all with more or less equal probability. One of these scenario's was a breakthrough for "true" thin film materials, such as a-Si, CIS or CdTe, and it could also be well possible that different technologies keep coexisting and find different markets (Goetzberger et al., 2002). However, c-Si technology has some physical limitations that guide the search into the direction of thin film technologies. For example, thin film materials just mentioned have a higher light absorption coefficient that c-Si, thus requiring less material in comparison with c-Si. Another advantage of some thin film materials is that they have a higher intolerance for impurities. This however does not indicate which thin film technology is more deserving of further development, and there are a number of factors that play a role in this issue. One of those is that research in, for example, a-Si has been going for over 20 years at this point in time, but it did not become a serious competitor with c-Si cells (Goetzberger & Hebling, 2002).

CIS at this time was considered particularly promising, as activities of Boeing led to CIS becoming the most efficient thin film solar cell (Goetzberger et al., 2002). In fact, it was considered to be the most promising thin film technology in this period, partly due to high efficiencies that were achieved abroad.

With regard to expectations on diffusion of the technologies, it seemed that it was expected that thin film technologies would gain ground relative to c-Si technology, although this was more on the long term, as can be seen from table 10.9. Perhaps more important here is to mention that the thin film technologies were all considered to be more or less equally respresented in the market share on the long term. Thus according to expectations, all thin-film technologies would become rewarding in the future.

Tabel 10.9: Development of market share of different Pv technologies (estimation) (Diehl et al., 2004).

Material	Market share in year		
	2000	2010	2020
c-Si and mc-Si	~90%	80–90%	~50%
TF-Silicon (a-Si; μ-Si)	~10%	~10%	20%
Concentrator Devices	n.a.	~5%	10%
CdTe and CIS TF	<1%	~5%	15-20%
Novel Devices	n.a.	~2%	~5%
Production vol. [GW]	0.3	3	12.4

10.5 Market formation

Silicon

In this phase policy initiatives were to be introduced that caused a takeoff of the market. This is indicated already in 1999 by the participation at the “Solar 99”, a three day fair held in Pforzheim, Germany. A record participation and the increase in visitors with definite investment decisions showed the established public interest into PV (HLH Heizung Luftung/Klima Haustechnik, 1999).

The worldwide share of crystalline cells in 2003 was about 93% (Managenergy,2004). In this phase vital policy measures were taken at a federal level, which signified the end of the uncertainty in the previous period and led to a considerable positive boost in the development of PV (Bruns et al., 2011). However, this breakthrough also caused some problems, such as rising module prices and limited production which naturally was not in favor of the diffusion of PV (Bruns et al., 2011). Also it turned out that some potential applications of PV were not welcomed by some societal groups (Bruns et al., 2011). The 100,000 roofs program however was not bothered by this.

100,000 roofs program

The 100,000 roofs program came into effect from 1 January 1999 under supervision of the Federal Ministry of Economics and in cooperation with SPD and the Greens (the two coalition parties in the government) (Bruns et al., 2011). The duration of the program was 5 years, and there were 10 years to repay the loan (of which the first two years interest free). The program provided investment grants to private contractors and the essential part of the program was that it provided low-interest loans (4,5% below market level) for those that installed PV systems. Also a part of the final repayment installment was waived (i.e. 10% of the lending volume), and 35% of the investment was thus covered (Bruns et al., 2011).These loans were given out by the KfW, a federal development bank, and was provided across Germany for construction and expansion of PV systems on surfaces of structures having a newly installed capacity of 1kW or more (Bruns et al., 2011). This program gave a considerable impulse to the market introduction of PV, as a total capacity of 346 MW in 55,000 systems were supported by about 1.7 billion euros, which finally got to 2.3 billion (Bruns et al., 2011). Nonetheless, the potential of the program was only to generate 4% of the energy production of single nuclear power plant, and the program was criticized by some associations and German Shell for not stimulating the demand sufficiently (Bruns et al., 2011).

Local support

Also, in the beginning of this period PV was supported by various states in Germany. For example, low interest loans were granted in Baden-Württemberg, and Saarland granted lump-sum investment grants (Bruns et al., 2011). Also campaigns were initiated such as the Solar Offensive project in Lower Saxony in 1999. In this program, which would run until 2003, 20 million DM is allocated (IWR, 2011). Another example is the Berlin Solar Campaign, which had as its aim the raising of awareness and the opening up of the market for PV. Prior to the campaign in 1998 300 PV installations were installed in Berlin with a total capacity of 1500kWp, mainly on single and two-family houses. In August 2001 there were 550 PV installations installed (Energie-Cités, 2001). Furthermore, following the professional press activities that were part of the program, the media profile of PV was greatly enhanced which was immediately visible in the form of requests for advise at the Solar-Service-Center (providing expert advice on grants, technical issues etc) and the Senate Administration for Urban Development (Energie Cités, 2001). However, the 100,000 roofs program did not give rise to extra support from the governments of the states. In fact, states (except four) that had previously supported PV now withdrew their support following the increase of federal support through the 100,000 roofs program (Bruns et al., 2011).

EEG

However, the 100,000 roofs program was about to get backup from the Renewable Energy Sources Act (EEG). When the EEG was introduced, the tariff increased with 8.25 cents/kWh to 50.6 cents/kWh initially for installations on rooftops smaller than 30kW (Bruns et al., 2011). The EEG was thus not directly compensating the initial investment, but rather the electricity generated by the investment. Network operators under this act were obliged to connect their grids to installations generating renewable energy, they must first purchase all renewable electricity generated, and they had to pay fixed rates for the generated electricity. Furthermore, the tariffs were fixed for 20 years (leading to investment security) and vary by renewable energy source (Stein, 2004). The combination of the 100,000 roofs program and the EEG made the generation of electricity through PV economically feasible for the first time. Vital for the tariff was the setup of the local cost covering models mentioned earlier (Bruns et al., 2011). A sign of the new economic feasibility can be seen in the increase of installed capacity, which grew from 12MW to 65MW in the period 1998-2001. The initial Electricity Feed-in Act (StrEG) had only a small effect, and the EEG was a significant improvement in the sense that the remuneration was higher at a rate of 50.6/kWh and was now decoupled from the electricity price (Bruns et al., 2011). The development of the tariff rates can be seen in figure 10.6.

		1991	1995	1999	2000	2001	2002	2003
Rooftop systems up to 30 kW		StrEG			EEG 2000			
Nominal compensation payment	Cent/kWh	8.5	8.8	8.4	50.6	50.6	48.1	45.7
Compensation payment in 2009 prices		11.9	11.0	10.0	59.3	58.1	54.5	51.2

Figure 10.6: Development of feed-in tariffs under the StrEG and EEG regulation in Germany (Bruns et al., 2011).

The rate of degression of the EEG was 5% which was based on the learning curve effect. This, however, led to a tariff of 45.7 cents/kWh in 2003, which was considered to be too low by the government. Thus, in 2004 the feed-in tariff was raised to 57.4 cents/kWh. The effects of the program can be clearly seen in figure 10.10.

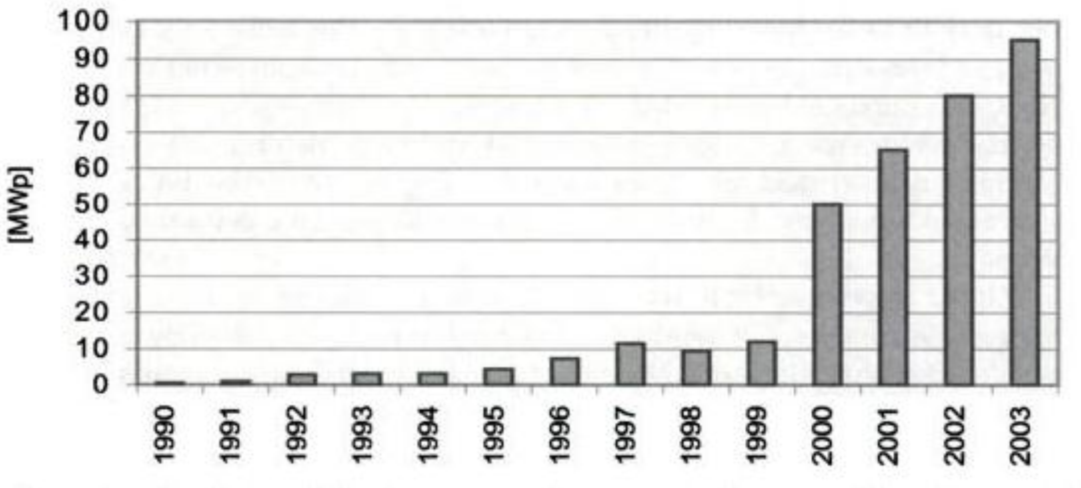


Figure 10.10: Annual installed grid-connected capacity in Germany in which the effect of the new legislation can be clearly seen in 2000 (Photovoltaic solar energy generation, Goetzberger, p173).

When the EEG was passed, 10,000 applications equaling a total capacity of 70MWp were received by the KfW development bank in one month (March 2000) (Bruns et al., 2011). Thus the passing of the EEG led to a high demand for funds from the 100,000 program. This caused problems in allocating the interest-free loans that were granted in the first two years of the loan, as it proved to be too difficult to deal with all the enquiries. Furthermore, the allocated 90 million euros for the year 2000 were insufficient, considering the large amount of applications (Bruns et al., 2011). Eventually this led the Federal Economics Ministry to stop the allocation of interest-free loans in April 2000, which subsequently caused uncertainty for investors (Bruns et al., 2011).However, new framework conditions were introduced not long after on the 10th of May 2000. Eligible costs for investment under these new conditions were limited to 6,750 euros, only installations up to 5kW received the interest-free loan in the first period of the loan, companies were only able to make use of 50% of the funding, and there were some other conditions as well (Bruns et al., 2011). Thus, a distinction was made between private and commercial investors, which sparked a lot of debate. Associations feared that because of the new conditions the amount of projects would drop, whereas politicians argued that these were necessary cuts in the expenditure. The inflamed debate complicated the situation and new applications or those unprocessed would not be processed that year (Bruns et al., 2011). However, in March 2001 the distinction between private and commercial investors was removed as the solar lobby was able to get new conditions through.

The market formation potential of the 100,000 roofs program is furthermore indicated by the demand in 2003, the final year of the program. As the program was approaching its end, investors were uncertain as to whether the benefits would continue in the future, and thus many wanted to benefit from the program while it was still possible; applications equaling 200MW had been received (Bruns et al., 2011). This again led to a freeze of applications, and the target for 2003 of 95 MW was subsequently increased to 150MW together with the corresponding funding volume (Bruns et al., 2011).

Furthermore, the cap of 350MW in the EEG program was removed in June 2002 and raised to 1000MW, resulting from the campaigning of solar energy associations and some politicians in the Bundestag for removal of this cap. Such a cap placed restrictions on the funding of PV systems under the EEG, which effectively meant that only a total of systems within the scope of 350MW would generate funding through the EEG, and thus the market volume was indirectly restricted. The removal of the cap led to greater investment security (Bruns et al., 2011).

The combination of the 100,000 roofs program and the EEG in this period was very successful, as figures show that the German PV market grew tenfold in this period 1999-2003 and German PV manufacturers expanded production capacities to meet the increased demand (Bruns et al., 2011). 363MW was installed, and the turnover in the PV sector increased from about 200 million to 500 million euro (Bruns et al., 2011). In table 10.7, the development of the installed capacity in Germany is shown under the different phases of policy.

	1990	1991	1992	1993	1994				
Installed capacity (MWp)	1	2	3	5	6				
New installations (MWp)		1	1	2	1				
Growth on previous year		100%	50%	67%	20%				
Market stimulated by:		1,000 Roofs Program							
	1995	1996	1997	1998	1999	2000	2001	2002	2003
Installed capacity (MWp)	8	11	18	23	32	76	186	296	439
New installations (MWp)	2	3	7	5	9	44	110	110	143
Growth on previous year	33%	38%	64%	28%	39%	138%	145%	59%	48%
Market stimulated by:	Municipal cost-covering compensation				100,000 Roofs program, Interim act on Photovoltaic energy				

Table 10.7: Development of installed capacity in Germany over the different phases (Bruns et al., 2011).

Also worth mentioning here is the revision of the Energy Industry Act in 1998, which gave access to the grid to every market participant (Niederprum & Pickhardt, 2002).

In 2001, the EU conducted the PVACCEPT program. This research program was set up in order to find out the level of acceptance of PV in “sensitive” applications, such as monuments under preservation or landscapes. For example, from the viewpoint of monument preservation PV was a foreign body on the structure not fitting within the rural landscape and from a landscape conservationist perspective “greenfield” PV plants were objectionable (Bruns et al., 2011). The research of the EU showed that one out of ten people of those surveyed did not find PV modules currently on the market aesthetically pleasing; however it was also found that three quarters of those surveyed did not necessarily object to PV installations on facades or rooftops of monumental structures if the design of the installation was suited to the building (Bruns et al., 2011).

Thin film

An interesting general observation here is the growing difference in market size for the different PV technologies. If we assume a PV system size of 3kW, and take the market size in 2003 we find that this amounts to approximately 150,000 installed PV systems, which is consistent with the order of magnitude of the 100,000 roofs program. Needless to say, these were for the most part systems using c-Si technology. For thin film technology to get a significant market share, tens of thousands of systems thus would have to be installed.

The market share for amorphous silicon cells was 6% in 2003, and a smaller part was for CIS and CdTe cells (1%). However, the share of amorphous cells seemed to be declining in 2003 (FVEE, 2003). Furthermore, in the beginning of this period the global share of thin-film technologies was slightly over 12 % of which the majority was made up by a-Si cells as can be seen in figure 10.11. The European market share of a-Si 10.5 % in 2000, 9.3% in 2001 (Diehl et al., 2001). The a-Si market experienced a growth of 25% in 2001, but the overall PV market growth was higher in Europe in 2002, which caused the share of a-Si to decline in the total market share. Only CdTe experienced an increase in market share around this time from 0,5 % to 0,7%. BP Solar, although not German, closed down all thin-film activities (a-Si and CdTe) in this period and Matshushita phased out the CdTe pilot production due to problems marketing Cd containing devices (Diehl et al., 2005).

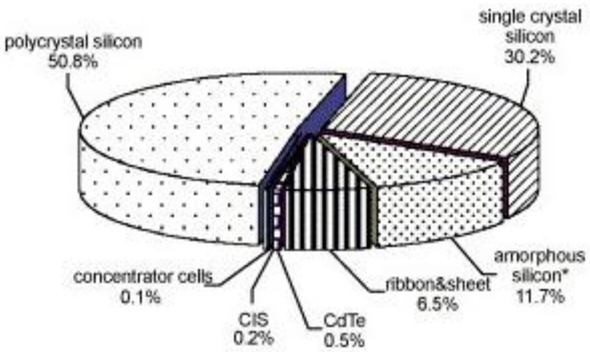


Figure 10.11: Global market share of different PV technologies in 2001 (Diehl et al., 2005)

Most firms in this period favored crystalline silicon technology over a-Si due to high failure rates and a degradation of efficiencies of this thin film technology (Diehl et al., 2005).

More specifically for Germany, a-Si also represents the largest thin-film market in Germany in this period (Diehl et al., 2005). PST (Phototronics) from Schott Solar had a production capacity of 3MW in 2002. Antec Solar was the second producer of thin-film technology with 1 MW of capacity for CdTe modules in 2002. However, Antec Solar went bankrupt in 2002. The insolvency of 2002 meant a blow to the CdTe market in Germany (Diehl et al., 2005). Antec Solar was succeeded by Antec Solar Energy GmbH which also focused on CdTe modules (250 kWp/month, maximum 10MWp/year) (Diehl et al., 2005).

Phototronics, which was producing a-Si modules, had a market in a variety of applications, including small sized applications such as watches, calculators etc. However, on larger scales also building integrated PV was offered (Diehl et al., 2005). Thus it seems that Phototronics with it’s a-Si technology tried to find specific niche applications within the niche of PV where a-Si could have an advantage over crystalline silicon technologies. For example in building integrated PV, an important feature is the temperature coefficient; a-Si modules for BIPV would deliver full power even at high temperatures (Diehl et al., 2005).

The cells of Antec Solar Energy however had a significantly lower efficiency compared to crystalline silicon modules (which is caused by the CdTe material), and was therefore relatively unattractive for rooftop applications (Siemer, 2003). Nonetheless, a market where this lower efficiency was not problematic was PV power plants in undeveloped areas (Siemer, 2003). This probably explains the insolvency of Antec Solar earlier in 2002. Even though private customers were not Antecs' target group, the remaining market apparently did not provide a good enough market earlier (Siemer, 2003).

10.6 Resources mobilization

In this period, the 100,000 roofs program went into effect. Resources in this program were mobilized through the KfW federal development bank mentioned earlier.

Also in some municipalities financial resources were mobilized in this period, although the municipal support decreased after the federal support went up in this period. Around 4 states retained their support despite the federal support that had now started (Bruns et al., 2011). An example of this is found in the Berlin Solar Campaign mentioned earlier, where the Senate Administration for Urban Development in Berlin mobilized around a quarter of a million euros for the campaign. Also four partners were involved in the implementation of the campaign (the solar industry federation UVS, the German Solar Energy Society DGS, Friends of the Earth Germany BUND and the energy consumers association BdE) which was supported by 118,000 euro in total in 2001 (Energie Cités, 2001). Furthermore the organizations themselves mobilized their own funds of about 100,000 euro. Also the Berlin Investment bank (IBB) played a role; in 2001 it had the command over more than 2 million euros in grant funds for the modernization and maintenance program for housing construction, which was supported by the Berlin Senate. Besides funding solar thermal installations, PV systems smaller than 5kWp in capacity were awarded grants of up to 1000 Euro/kWp. Furthermore, the energy supplier of Berlin, BEWAG, pays 51 euro cents for every kWh fed into the grid generated through PV over a period of 20 years. The rate depreciates with 5% every year for installations built onwards from 2002 (Energie Cités, 2001).

Furthermore, in this period the cap of 350MW for the EEG was raised to 1000MW as mentioned earlier, which led to greater investment security (Bruns et al., 2011). Nonetheless, it was still difficult to get bank loans for solar plants (Bruns et al., 2011). However, as the 100,000 roofs program was approaching its end, there was the threat of a gap in the funding of PV. Naturally, the PV sector called for extending the 100,000 roofs program or some other provision of funding. Furthermore, in a study that evaluated the program conducted by the Federal Environment Ministry, it became clear that a lack of phase-out measures for PV support would lead to the kind of situation experienced at the end of the 1000 roofs program (Bruns et al., 2011). The insecurity after the end of the 1000 roofs program led to a decrease in industry engagement, and another such an event would threaten established structures and particularly small and medium enterprises lower down the production chain (Bruns et al., 2011). In order to avoid a breakdown of the PV market, eventually the Interim Act on Photovoltaic Energy was adopted in January 2004.

Financial resources mobilization for market formation from a government perspective is summarized in table 10.8.

Tabel 10.8: Overview of financial resources in Germany allocated for PV market formation (Stubenraumer, 2003).

Federal Government	Kind of Funding	Name of Programme
BMWA / BAFA	Subsidy: up to 3000 Euro/ installation	Sun at school, general programme
BMU/ KfW BMU/ KfW DBU (foundation)	Low interest loan (1,91%) Low interest loan (3,75%) Subsidy	100 000 Roofs Solar Power-Programme Environmental and CO_2-Reduction Programme 300 Parishs for Solar Energy
Federal States		
Baden Württemberg	No general funding	
Bayern	No general funding	
Berlin	No general funding	
Brandenburg	No general funding	
Bremen	No general funding	
Hamburg	No general funding	
Hessen	Project support for PV plants outside KfW	Low interest loans for grid-connected PV systems
Mecklenburg-Vorp.	No general funding	
Niedersachsen	1. Loans 2. Subsidies for PV systems in some regions (Hannover) 3. Subsidies for PV systems in agriculture	1. Loans for energetical modernization of buildings 2. Max. 7 670 Euro per system
NRW	Subsidies for PV systems	REN Programme
Rheinl.-Pfalz	No general funding	
Saarland	No general funding	
Sachsen	No general funding	
Sachsen-Anh.	No general funding	
Schleswig-Holstein	Further reduction of interest rates of some KfW programmes	
Thüringen	Subsidies for PV-systems	

Thin film

An example of a startup in CIS thin-film technology in this period is Sulfurcell, which emerged as a spin-off from the HMI institute which developed its technology in 1999. However, it was difficult for the spin-off to get financing in order to go commercial, as there was initially no interest from the industry since the path from development to industry seemed too long (Wengenmayr & Bührke, 2011). It seemed that this was due to the inexperience of the entrepreneurs in making their product interesting from an entrepreneurial and business perspective, as they were trained only as scientists. After some time however they learned how to promote their idea from a business perspective: "Sulfurcell intends to produce solar modules for 50% less than those currently on the market" (Wengenmayr & Bührke, 2011). When other actors from the glass sector and the metal construction sector, entrepreneurs and finance investors got convinced of the potential the financing started. However they were not there yet, as the enterprise was a risky investment due to the completely new technology. At that time, banks did not finance the project, and venture capitalists were reluctant due to the collapse of the New Economy (Wengenmayr & Bührke, 2011). After Sulfurcell reduced the risks for investment and offered service in return (i.e. disclosing know-how, mapping out sales channels, stakes in the profit etc.) suitable partners were found in the form of public funding resources, industrial investors, and venture-capital providers. Furthermore, shareholders at present include the investment branch of the utility Vattenfall. a specialist for building services and the

Berliner Energy Environment Fund (Wengenmayr & Bührle, 2011). Since there were several years between the laboratory research and pilot plant production, and several more years before net profit could be made, the fact that there were investors shows that apparently there was trust in the economic viability of the CIS technology developed at Sulfurcell.

10.7 Advocacy coalitions

Although the 100,000 roofs program was initially started, it seemed another driver was needed (Palz, 201a0). Efforts were made by EUROSOLAR to increase the feed-in tariff. An important ally from the government, Oskar Lafontaine, at this time was no longer a finance minister and thus initiative from the government was not to be expected (Palz, 2010a). The aim was now to extend the Electricity Feed Act, which was already existing. What helped the PV sector despite the changed finance minister in this period was the change of government in 1998 as a new orientation of the energy policy found its way; a cross-parliamentary group ("solar parliamentarians") alliance was started by Hermann Scheer from the SPD and Joseph Fell from the Greens which had the support of about 50 members from parliament (Bruns et al., 2011). From 1999, four members of the Bundestag (two from SPD, including Herman Scheer, and two from the Greens) were working on a draft bill, and subsequently the famous Renewable Energy Act (EEG) was formed. For this bill, the SPD and Green party parliamentary groups were won over to support it in 1999, and the final vote for it was scheduled early 2000 (Palz, 2010a). Instrumental in getting the majority in this regard was to limit the 99 pfennigs per kWh, which was proposed as a guaranteed price but seemed utopian, to the amount of roofs from the 100,000 program which was at that time running (Palz, 2010a). However, there was a last minute attack on the law, two weeks before the final vote. It was claimed that the Renewable Energies Act (EEG) would violate the EU's market rules and that it was incompatible with European law. For that reason, the cabinet called upon EUROSOLAR to get permission from the EU Commissioner for Competition. Thus, the economics and finance ministers proposed to delay the vote for the new bill, in order to have time for negotiating the bill with the European Comission. This however seemed to have a greatly negative impact on the bill, and it could even mean the end of it. As Hermann Scheer puts it: "*I knew only to well that this would spell the end of the bill. Things became to verbal blows between minsters and myself in the parliamentary-group session three days of the envisaged final vote in parliament. I moved to bring the bill to the final vote unchanged and without delay, and won the vote by about 90%."* (Palz, 2010) . The Act was implemented in April 2000. Nonetheless, in the same month already the European Commission filed a lawsuit against the Act. However, in March 2001 the European Court of Justice dismissed it, and thus the Renewable Energies Act (EEG) and with it PV had taken off (Palz, 2010a). At the start of the program, the total installed capacity was about 50 MW. For comparison: Just within the year 2009 there were more than 3000MW of installations , which shows the take-off that took place after the 100,000 roofs program and the EEG were implemented (Palz, 2010a).

However, towards the end of this phase, the 100,000 roofs program was coming to an end. Since this created uncertainties for the PV sector, Hermann Scheer, the founder of EUROSOLAR and a key player in getting the 100,000 roofs program through, was calling for a 1 million roofs program as a follow up to the 100,000 roofs program. However, worries at the time seemed to be mostly focused on whether or not the EEG (the Renewable Energies Act) would survive the elections (Siemer & Kreutzman, 2002). However, the elections in 2002 turned out to be very favorable for the PV sector, as SPD (Hermann Scheer was in this party) and the Greens (Josef Fell was in this party) continued to form a coalition after the election. The conservatives (CDU/CSU) along with their potential coalition partner FDP were thought to be the winners of the election for quite some time. Economic experts from these parties were of the view that renewables should compete against each other (rather than receive the protection they did), which most of the PV industry would consider as harmful for the PV sector (Siemer & Kreutzman, 2002). Furthermore, the renewable energies within the federal government came under control of Trittin from the Greens, which was considered as favorable for the PV sector (Siemer & Kreutzman, 2002).

It can be said that the newly elected government worked hard to secure support for renewables and it was one of the most important forces facilitating the diffusion of PV in this period (Bruns et al., 2011). Furthermore, in cooperation with the Federal Economics Ministry it was able to get the 100,000 roofs program through (Bruns et al., 2011). With regard to the EEG, the Federal Environment Ministry and other parliamentary groups in the Bundestag campaigned for the raising of the remuneration rate per kWh in the EEG, which was important for the breakthrough of PV (Bruns et al., 2011).

The role of the associations was mainly to support and strengthen the ministries, the parliament and the federal government (Bruns et al., 2011). In 1998, the Solar Industry Trade Association (UVS) was founded. The German Solar Energy Association (BSE) and the German Solar Industry Association (DFS) merged and became German Solar Sector Association (BSi) in 2003 (Bruns et al., 2011).

10.8 Conclusion

In this phase very important market incentives were introduced which caused a strong growth in installed capacity. This attracted new companies in both the silicon and thin film sector. Especially characteristic for this development is the entrance of companies having a specific focus on PV. It is very much understandable that the c-Si sector attracted much new activities, as these were still the most suitable modules for rooftop installations in terms of efficiency and the available space on a rooftop, which in the end come down to economic considerations. However, apparently also thin film technology was considered as having potential to benefit from this development, especially CIS technology. Nonetheless, production for this type of cell was not in the stage of mass production in general, only for one company (Würth Solar). Such entrepreneurial activities were of prime importance to facilitate the growth that was taking place and to position Germany for future (thin film) developments in the market.

Just as c-Si modules represented the largest market, it also took relatively most of the research funding as was pointed out. The amount of published researched seemed to be rising, while this was not the case for the thin film technologies. Cost reduction was a major goal of the R&D done in this period, and it was achieved among others through thinner wafers and higher efficiencies. This was also important due to the silicon shortage. PV technology improved slowly but steadily. Like in other periods, there was collaboration going on between different research institutions, but also between industry and research institutions. This seems to have been more instrumental for thin film technology such as CIS cells than for c-Si, which is obvious from the fact that firms such as Sulfurcell, Solartechnik and Würth among others have a significant part of their origins in R&D institutions. Crystalline silicon cells on the other hand were already on the market and required less new expertise, although this seemed to have been changing by the shift towards thinner materials, which brings about new R&D issues. Although in this period the thin film crystalline cells were still in laboratory stage, such good established connections between research institutes and industry have proven to be instrumental in bringing new technology to the market, as we have seen with CIS. Germany was also in a good position for PV research in a general sense, as it had many active institutes with a broad range of topics. Costs of systems were slowly but steadily reducing, thus making them more and more competitive.

The 100,000 roofs program seemed to have indirectly pulled R&D towards c-Si, or at least it has reinforced this mechanism, due to the fact that c-Si modules were most suitable for application on private household rooftops. While c-Si in this way saw a reinforcing of its relevance, within the field of c-Si the silicon shortage was pulling resources towards this subfield of thinner c-SI wafers within c-Si. This was of course a positive development, since materials reduction meant a further reduction in costs, which was necessary in order for solar cells to become more competitive. Support for R&D was relatively focused on c-Si cells, and less so on thin film technologies. This, of course further favored cost reductions in the field of c-Si PV. Together with the 100,000 roofs program and the EEG, this definitely put c-Si technology in a further advantage, as the installed capacity and thus the production of modules got a boost. Thus the 100,000 roofs program, and also the EEG, indirectly favored c-Si cells in this period as was repeatedly mentioned, due to the fact that other types of technologies were not competitive with c-Si cells. The market for c-Si cells experienced a boost and PV technology became competitive for the first time due to the low interest loan (which was partly a gift) and the remuneration through the EEG. Obviously, PV technology was still very much dependent upon financial support, which was partly granted by the KfW in Germany in the form of low interest loans. Activities of advocacy coalitions were vital in this regard. Although there was no explicit focus found on c-Si technology, indirectly this was the case due to the nature of the proposed policy programs that suited c-Si technology more. Nonetheless, limitations from c-Si technology or disadvantages were leading to developments in the lab and less so in the market in the field of thin film technology, especially CIS.

11. 2004-2012

11.1 Entrepreneurial activities

In table 11.1 production figures are given in 2006 and 2010 to illustrate the general growth of the PV industry.

Tabel 11.1: PV production figures in 2006 and 2010 in Germany (Wissing, 2007;Wissing, 2011).

	2006	2010
Production of cells	500 MWp	2656 MWp
Production of ingots & wafers	300 MWp	1990 MWp
Production of feedstock silicon	6200 t	31300 t

The figures make no distinction between thin film and conventional c-Si technology, but nonetheless show that German industry was capable of expanding its activities in order to provide for the growing demand. Nonetheless, Germany was also a main market for Asian modules (Wissing, 2007), thus reducing the relevance of German producers to a point where they were apparently not essential, since modules could also be imported from other countries, which is a consequence of globalized markets.

In this period, the fully integrated company Sovello (2005), module manufacturer Centrosolar (2007) and wafer, cell and module manufacturer Bosch Solar (2008) have also entered the market But not only did companies flow into others, also did companies change or add to their core business. This mainly happened in response to the silicon shortage; for example in 2005 Solar Fabrik, which was initially focused on module manufacturing, in response to the silicon shortage expanded its activities from wafer trading to module manufacturing. When the availability of silicon was increased in 2008/2009 however, Solar Fabrik refocused on module manufacturing (Solar Fabrik, 2011). Similar instances occurred at Schott Solar, which started ingot production in 2006, and at Solarworld which expanded its activities towards solar silicon recovery (Solarworld, 2011) in the same period. An overview of companies active in 2008 in the German crystalline silicon PV manufacturing market is given in table 11.2.

Table 11.2: Overview of manufacturers in the German crystalline silicon value chain (Invest in Germany, 2008).

Value Chain	No.	Company	Location	Capacity 2008 [MWp]	Current Empl.
Silicon	1	Wacker Chemie	Burghausen	10,000t	960
	2	Scheuten Solar World Solizium	Freiberg[1]	1000t	n/a
	3	Sunways	Spreewitz[1]	1000t	n/a
	4	PV Silicon	Bitterfeld-Wolfen[1]	900t	20
	5	Joint Solar Silicon	Rheinfelden[1]	850t	10
Wafers	6	PV Silicon[2]	Erfurt	290	160
	7	ASi Industries[3]	Arnstadt	180	480
	8	Wacker Schott Solar	Alzenau, Jena[1]	120	300
	9	Q-Cells	Thalheim[1]	80	10
	10	Mola Solaire	Pasewalk[1]	n/a	n/a
Cells	11	Q-Cells	Thalheim	760	1900
	12	Ersol Solar Energy	Erfurt, Arnstadt	220	300
	13	Solland Solar Cells	Aachen	170	300
	14	Sunways	Konstanz, Arnstadt	120	290
	15	Arise Technologies	Bischofswerda	35	10
	16	Scheuten Solar Cells	Gelsenkirchen	35	80
	17	Solarwatt	Heilbronn	15	60
Modules	18	Solon	Berlin, Greifswald	260	400
	19	Aleo Solar	Prenzlau	170	425
	20	Solar-Fabrik	Freiburg	130	290
	21	Solarwatt	Dresden	120	430
	22	Scheuten Solar Technology	Gelsenkirchen	90	140
	23	Centrosolar / Solara	Wismar	80	160
	24	Heckert Solar	Chemnitz	60	120
	25	Webasto Solar	Landsberg/Lech	35	20
	26	Asola	Erfurt	30	100
	27	Algatec	Elsterwerda	15	65
	28	Solarnova	Wedel	10	30
	29	GSS	Löbichau	10	30
	30	PVflex Solar	Fürstenwalde	5	30
	31	Schüco Solar	Bielefeld	5	450
Fully Integrated	32	Solarworld[5]	Freiberg	450/300/250	1200
(Wafers/Cells/	33	Conergy[2]	Frankfurt (Oder)[1]	250/250/250	370
Modules)	34	Schott Solar[5]	Alzenau	160/275/200	450
	35	EverQ	Thalheim	100/100/100	1000

According to an estimate of the German Solar Sector Association (BSW), about 15,000 firms are active in this field and employ about 70,000 people in 2009 (Jeznita, 2009). From these firms, over around 100/200 are active in the production of modules, cells and components, while the overwhelming majority are so called handicraft enterprises. In 2008, a total revenue of about 8 billion euros was generated by the sector. In 2010, 69 companies were active in PV production (note that this excludes equipment manufacturers etc.), which had a total turnover of 12,2 billion EUR in 2010 (Wissing, 2011). Evidently, the number of companies and their activities had experienced high growth after the EEG and 100,000 roofs program. From table 7 it can furthermore be seen than German companies were active in practically every part of the supply chain, although installation companies are not mentioned but nonetheless they numbered many

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Entrepreneurial projects

A large number of projects have been conducted in Germany where c-Si solar cells have been applied, varying in size and type. Worldwide the grid-connected application of PV has seen the largest growth and by far the largest part of new PV capacity is grid-connected (Solar Technologies, 2011). Examples of such grid-connected projects are large solar power plants, where a large area of land is covered with solar cells. Other examples are urban projects, where roofs or facades are covered with solar cells. With regards to grid-connected solar power plants in Germany, they vary in size considerably. Germany is home to some of the worlds' largest solar power plants (about 18 of the 50 largest power plants in the world are German). In these large solar parks (>20 MW), a search revealed that crystalline silicon solar cells are used the most (more than 60%). Smaller open-space projects that utilize crystalline solar cells are also found. The majority of PV projects in 2009 in Germany were, however, small and medium sized installations on rooftops (83%), with 43% of 30 kWp or less installations. (PWC, 2011). This is in contrast with, for example, Spain, where the majority of PV is installed on large solar farms (93%). Since the newly installed capacity in was 3,8 GWp, and 43% of this was 30 kWp or lower on rooftops, this implies that tens of thousands of rooftop PV systems were installed in 2009. This information, however, is not specific for silicon wafer cells but for German PV in general. Nonetheless, since silicon wafer solar cells still represent the largest market overall and specifically in the sector of classic roof systems (Wirtz & Janssen, 2010), it gives a good image of the order of magnitude of annual urban installation rates using silicon wafer cells. Around 53,000 people are estimated to work in the German PV industry around 2009 (BMU, 2009).

Thin film

Around the beginning of the period, a few companies had a focus on thin-film solar cells (Diehl et al., 2005). Two manufacturers had production lines at this time: the PST (Phototronics) division of Schott Solar with a-Si thin-film technology and Antec Solar GmbH with the CdTe technology. Würth at this time was running a pilot line for CIS cells (Diehl et al., 2005). Later on more companies joined the thin-film market. For example, Sulfurcell (which focused on CIS modules) shipped its first modules in 2005, although it could not be said that it had really entered the market at the time. In 2011 it had secured $25.6 million of equity funding in order to expand its activities and get its thin-film PV modules (12.6% efficiency) into the market (Nusca, 2011).

In 2007, CIS was still the only thin-film PV material being manufactured on a high quality level in comparison to polycrystalline silicon (Dimmler & Wächter, 2006).

At present, for ground mounted projects, both thin-film and silicon cells seem to be widely used (Wirtz & Janssen, 2010). A search through the project references of a renowned installer in Germany, Gehrlicher, reveals that in 2007-2011 the majority of their ground mounted projects (over 70%) were using thin-film cells, the majority of which were manufactured by the American company First Solar. First Solar makes CdTe thin-film cells (First Solar, 2011).

The Würth Solar CIS pilot plant achieved efficiencies of around 11-11.5 % in 2004. As mentioned in the previous phase, the annual production in of the pilot plant reached its maximum capacity in 2004. Thus around 2004-2005, a decision was made at Würth Solar to build a 15MW plant for manufacturing CIS modules, which clearly indicated it had decided to start mass-production in the area of CIS technology (Powalla et al., 2005). In 2006, Würth Solar as the first company actually started the mass production of CIS solar cells (Wirtz & Janssen, 2010).

In 2008, Shell Solar divested its crystalline silicon solar activities to Solarworld (Green Car Congress, 2006) due to a focus on CIS thin film technology. Later, however, Shell completely gave up its solar activities (The Guardian, 2009).

At present, there are a number of thin-film silicon PV companies active in Germany. Notable ones include Schott Solar (cells and modules), Ersol Thin Film, Malibu GmbH, Inventux Technologies AG, Signet Solar, Sontor GmbH (QCells) and Masdar PV. A table with the German companies active in 2008, along with their capacities and number of employees, is given in table 11.3. It is clear in comparison with the data shown earlier that the capacities and amount of employees in 2008 in the thin-film market are much lower than in the crystalline silicon PV sector. Furthermore, it can be seen that in the crystalline silicon PV sector more specialization took place (i.e. silicon, wafers, modules), in spite of some fully integrated manufacturers. This could be attributed to the time which c-Si PV technology got to develop in comparison with thin-film, which is commercially much younger.

Table 11.3: Companies active in Germany in the thin-film market in 2008 (Invest in Germany, 2008).

Value Chain	No.	Company	Location	Capacity 2008 [MWp]	Current Empl.
Thin Film					
Poly-Si	36	CSG Solar	Thalheim	20	150
a-Si	37	Sunfilm	Großröhrsdorf[1]	60	50
a-Si/μc-Si	38	Ersol Thin Film	Erfurt	40	180
	39	Malibu	Osterweddingen[1]	40	150
	40	Schott Solar Thin Film	Jena, Putzbrunn[1]	30	160
	41	Inventux	Berlin[1]	30	n/a
	42	Sontor[4]	Thalheim	25	60
	43	EPV	Senftenberg[1]	25	n/a
	44	Signet Solar	Mochau	20	70
	45	Intico Solar	Halle[1]	n/a	n/a
	46	Masdar PV	Arnstadt[1]	n/a	n/a
CIS	47	Global Solar Energy	Berlin[1]	35	n/a
CIGS	48	Johanna Solar Technology	Brandenburg	30	100
CIGSSe	49	Odersun	Frankfurt (Oder), Fürstenwalde[1]	30	90
	50	Würth Solar	Schwäbisch Hall	30	220
	51	Solibro[4]	Thalheim[1]	25	150
	52	Avancis	Torgau[1]	20	60
	53	Solarion	Leipzig	10	35
	54	PVflex Solar	Fürstenwalde	Pilot	130
	55	Sulfurcell	Berlin	Pilot	120
	56	CIS-Solartechnik	Bremerhaven	Pilot	20
	57	Nanosolar	Luckenwalde[1]	n/a	n/a
CdTe	58	First Solar	Frankfurt (Oder)	175	500
	59	Calyxo[4]	Thalheim	25	40

In 2010, Sunfilm AG filed for insolvency. As it was still in an early stage of market entry, the discussions on the feed-in tariff and the market conditions created a difficult situation for the firm and lead shareholders to stop their financial support (Sunfilm, 2010).

Competition

For roof systems, a search through the database of Gehrlicher, a renowned German installer of PV systems, shows that almost every system installed before 2006 is based on crystalline silicon technology (Gehrlicher, 2011). Only from 2007, thin-film solar cells start to take a significant share in the installed PV roof systems installed by Gehrlicher. In some years after that until 2009 the majority of modules (for ground mounted and roof systems) is based on thin-film technology from First Solar (an American firm), although the smallest projects (which are on roofs) seem to use crystalline silicon modules. Interesting to see is that in 2010, this trend reverses with regard to roof systems and since this year Gehrlicher uses modules from a fully vertically integrated Chinese manufacturer of silicon solar cells, Yingli Solar, in their roof systems. In 2011 again this changes and Gehrlicher uses both crystalline modules from Yingli and thin film modules from First Solar on a reasonably even basis. (Gehrlicher, 2011).

11.2 Knowledge development

11.2.1 Learning by searching (R&D)

In figure 11.1 the development of the number of German papers on different PV technologies is given for this period (based on findings from Scopus).

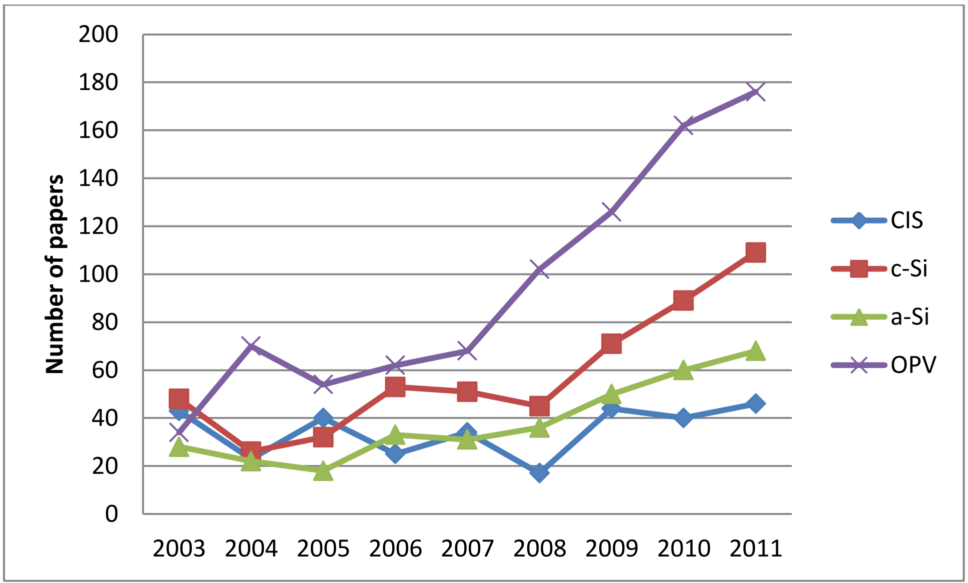


Figure 11.1: Number of German papers on different PV technologies this period (taken from Scopus).

National R&D program

The Fifth Energy Research Program was launched in 2005. It was launched by the Federal Research Ministry and the Federal Environment Ministry jointly for the first time, and focused on the increasing of efficiency, reduction of material use and the automating and optimization of manufacturing technologies, with regard to both silicon and thin-film solar PV technology (Bruns et al., 2011). The BMU funding will be primarily focused on research in the pre-competitive stage, with all German companies able to access the findings. Thus, the allocation of funds is done in such a way that greater emphasis is placed on medium and long term than on short term application (Wissing, 2011). The focus of the program is still on silicon wafer technology, and thin film technologies with regard to silicon and CIS take a second but significant place (Wissing, 2011). A distribution of the approved funding in the Fifth Energy Research Program can be seen in figure 11.2.

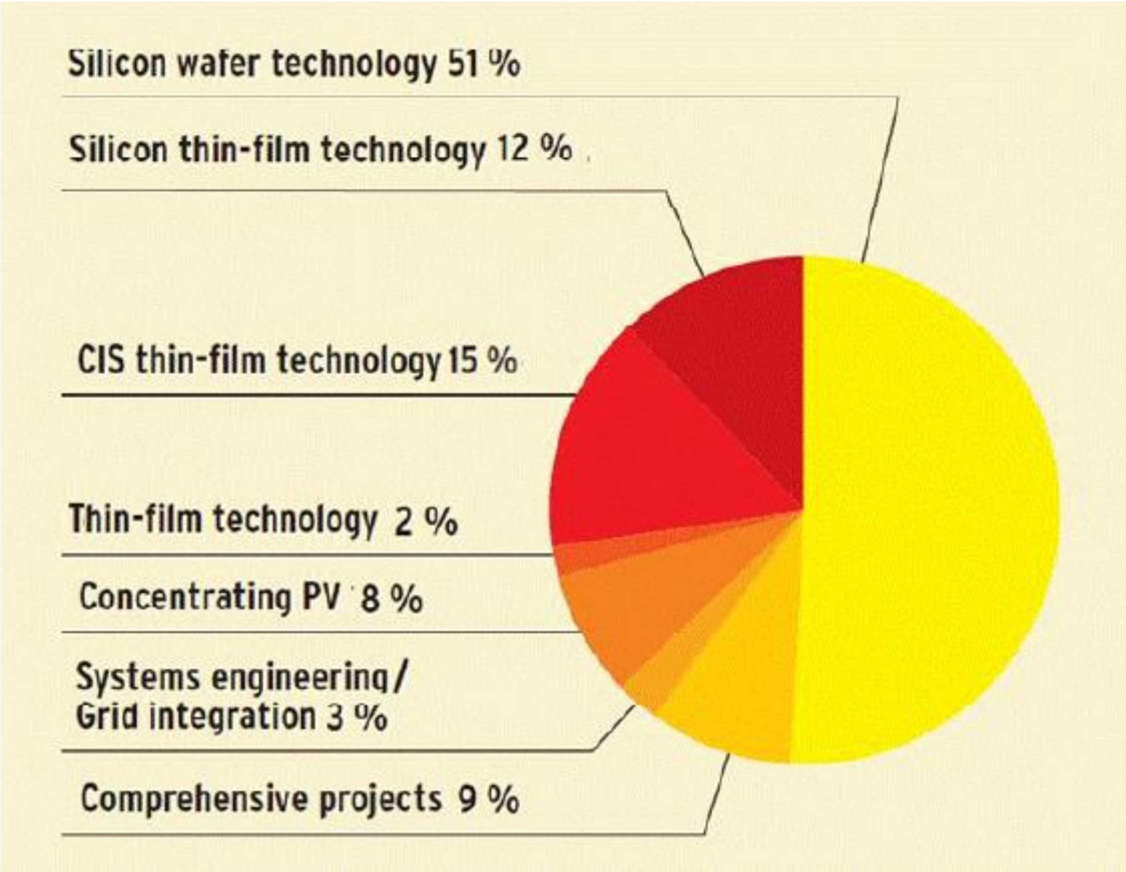


Figure 11.2: Overview of newly approved funding in the Fifth Energy Research Program in Germany (Wissing, 2011).

Germany has a strong R&D base with regard to PV: There are 50 state-of-the-art research institutes and university faculties doing research in PV technology and 290 solar patents were registered in Germany in 2010 (GTAI, 2011). Even though silicon wafer cells have been the most extensively researched PV technology, it is still a priority in research, for government (depending on the ministry) and industry. The research done for silicon wafer solar cells can be categorized into different categories. For governmental institutions however, the priorities for silicon wafer solar cells seem to be different than for some industrial players. For example, governmental focus with regard to research on silicon wafer cells seems to be on low-cost manufacturing and new cell structures, whereas for example Q-Cells holds that the standard architecture of silicon wafer cells still has plenty of room for improvements in with respect to cost and efficiency (Wawer et a., 2011). On the 26th PV conference, held in Hamburg in early September 2011, quite some papers were presented on silicon wafer based technology (345 papers). Part of these papers originated from solely German organizations, others were of mixed origin (i.e. cooperation between institutes from different countries) and others were of foreign origin. Due to the limited information given in the database it was difficult to estimate the amount of German papers presented on the 26th PV conference with regards to silicon wafer technology. This was easier to do with the information given in the proceedings of Silicon PV 2011 conference. This contained a hundred papers on silicon wafer technology, of which around 65 were estimated to be German, all recent scientific work. This research is conducted by research institutes, universities and firms. The BMU department of the German federal government allocates most of its PV related funding to silicon wafer technology (51%) (GTAI, 2011). The BMBF department of the German federal government focuses more on basic research for thin-film cells.

Research projects that involve companies and research institutes on silicon-wafers are funded by the BMU. A particular aim is cooperation between research and industries in order to facilitate the introduction of new techniques. Furthermore, quality assurance is a priority in order to give German companies an edge over the international competition. Also methods to get higher efficiencies at lower costs are researched in such projects, as well as new structures with higher efficiencies (BMU, 2009).

Although silicon solar cells were thought to be almost fully developed (e.g. BMBF, 2005), this seems not to be the case. Most progress up to now in solar cells has been achieved through the further development of the wafer technology dominating the market, but a lot more cost cutting is possible (FVEE, 2008). In order to do this, new technologies must be developed that focus on using thinner wafers, new kinds of cell structures, higher efficiencies, simplified processing and lower production costs of the silicon used for solar cells and lower cost of production of thin silicon wafers (FVEE, 2008). So evidently, it is not a matter of getting the system to work (which it already does for decades), but purely to drive the costs down. *Crystalline silicon*

From the development number of German papers in Scopus on crystalline PV depicted in figure 589, it appears that c-Si research experienced a dip in 2003-2004. The reason for this could be the Fifth Energy Research Program that started in 2005; i.e. to secure funding for projects research institutions had to know the criteria for project funding and thus they waited until these criteria were made public before initiating new projects. This assumes that these criteria were made public before the start of the program, which is a reasonable assumption given the loss of time if this were not the case. For the rest of the period there had been an increase, and c-Si research was also given priority in the Fifth National Energy Research Program.

Leading research institutions with regard to c-Si technology were the Julich Research Centre, the Fraunhofer Institute and the Helmholtz Centre. Topics include hetrojunction mc-Si/a-Si thin film cells (which drive down costs, but have lower efficiencies) and multicrystalline cells. Also industrial R&D appeared in published form, for example from RWE (although this stopped later on in this period, presumably after being taken over by Schott Solar), Sunways (on back contacts, back surface field), Schott Solar (e.g. thin film silicon solar cells) and CSG solar GmbH (i.e. c-si solar cells on glass).

The research found includes basic and applied research.

Thin film

As thin film technologies continued to be developed, efficiencies also rose as can be seen for example in figure 11.3, which shows the learning curve for the company Sulfurcell, which produces CIS modules.

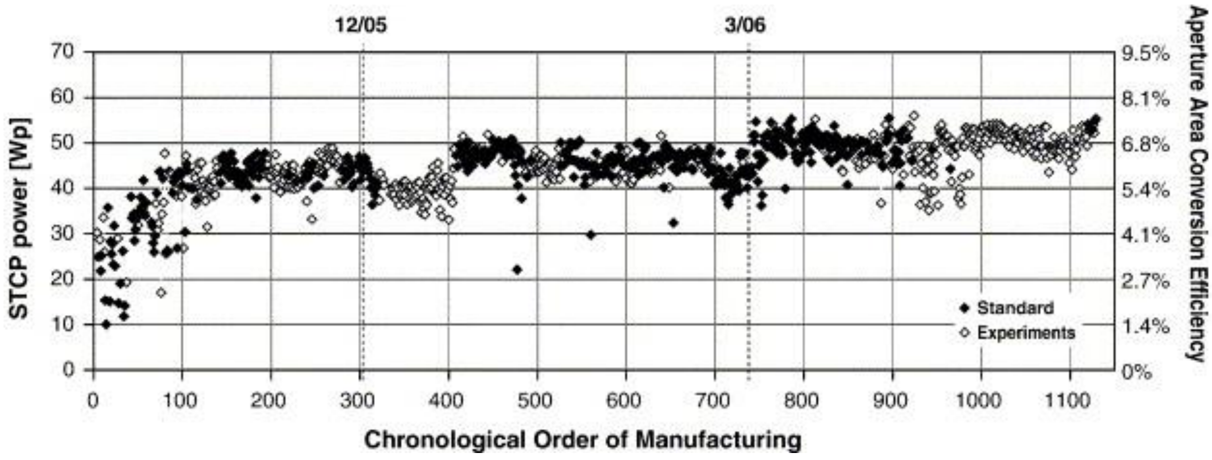


Figure 11.3: Learninc curve for Sulfurcell, a CIS modules producing company (Meyer et al., 2007).

Organic solar cells

As can be seen in figure 11.1, organic solar cells really experienced a boost in this period in terms of the amount of published papers. In fact, this even surpassed all other PV technologies from early on this period. With regard to organic solar cells, the main research topics are encapsulation (mainly for flexible solar cells), module wiring, further development of current cell concepts, modified production technologies and evaluation of new organic semiconductor systems with improved absorption of incoming radiation and optimization of charge transport (FVEE, 2008). Main institutions involved were the Technical University of Dresden, the Fraunhofer Institute, the Helmholtz Institute and the University of Freiburg, although many other institutions also contributed although to a lesser but significant degree.

Also industrial firms were found to do research. For example, it seems that Siemens AG was involved until early in this period (around 2004), before it sold its OPV activities to Konarka (Siemens, 2012). Another example is AIXTRON AG, and in recent years also Robert Bosch GmbH (known as Bosch). Another active company in OPV is Heliatek GmbH.

Research on OPV is both basic and applied, indicating that commercialization is under its way, although not yet achieved in a broad sense (Tress et al., 2011). Note that organic PV was not significantly funded by the BMU compared to silicon and thin film technologies, as was shown earlier. It can then be questioned why organic PV experienced the largest growth of papers in this period, but in a relative and absolute sense? The answer for this seems to be the fact that organic PV *was* sponsored by the BMBF and to a much larger degree by industry. From 2008 to 2015 it appears the BMBF will be supporting organic PV with 60 million euros, with the agreement in place that involved companies will contribute 5 times as much, thus amounting to about 300 million euros (Research-in-Germany, 2012).

11.2.2 Learning by doing

Evidently a lot has been learned with regard to solar cell manufacturing in a technical sense. This can be seen for example in the reduction of the system price of the years: From 2007 to 2011 the average roof system price in Germany decreased approximately 40% (GTAI, 2011). Data on the price per Wp in Europe for crystalline modules shows a decrease of approximately 40% from early 2008 until early 2010. A less recent study conducted in 2004 shows a progress ratio for German silicon modules of 90% (Needs Project, 2006) , which implies a 10% reduction in costs for each doubling of the cumulative output. Furthermore, a study showed that the average price for rooftop systems of less than 100 kW reduced 25% from 2008 to 2009, and 13 % from 2009 to 2010 (Wissing, 2011). In figure 11.4 recent the cost developments from 1980 until 2009 are shown for silicon modules.

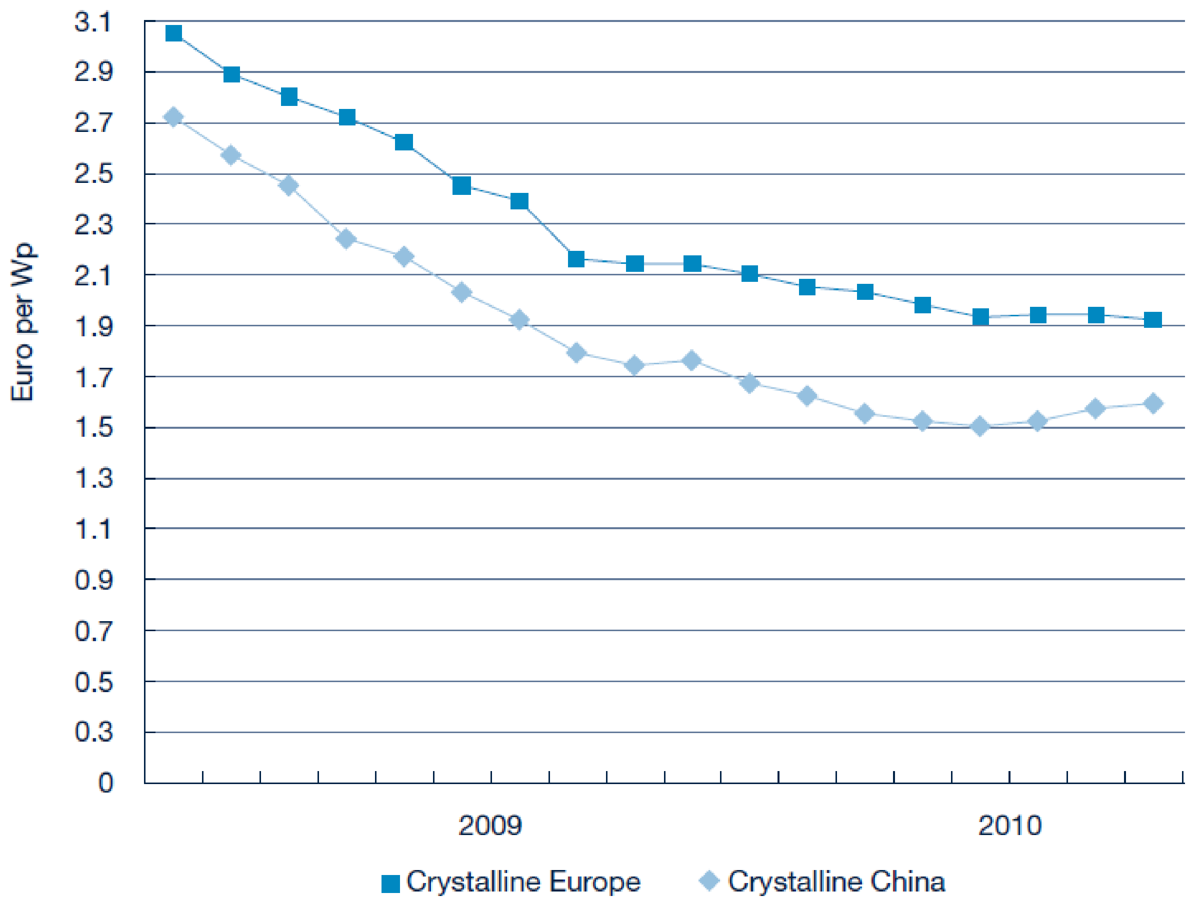


Figure 11.4: Development of crystalline silicon module prices in Europe and China (PWC, 2011)

However the progress ratio for German modules lagged behind the global average (Needs Project, 2006. This could be explained by the feed-in tariff, which could make manufacturers less motivated to compete with each other on lower prices. Another explanation is that the induced market growth (as a result of the policy programs) is too high for the PV industry to benefit optimally from learning by doing effects. Thus it is argued that in order for learning by doing effects to be optimally utilized, the growth should not be excessive (Wand & Leuthold, 2011).

There is some difficulty here however in the attribution of cost reductions to learning by doing, as evidently learning by searching played a major role in a number of ways in driving down costs (e.g. higher efficiencies that were achieved as well as thinner materials). Therefore more research is needed in this specific issue in order to gain more insight in the proportion of causes in cost reduction.

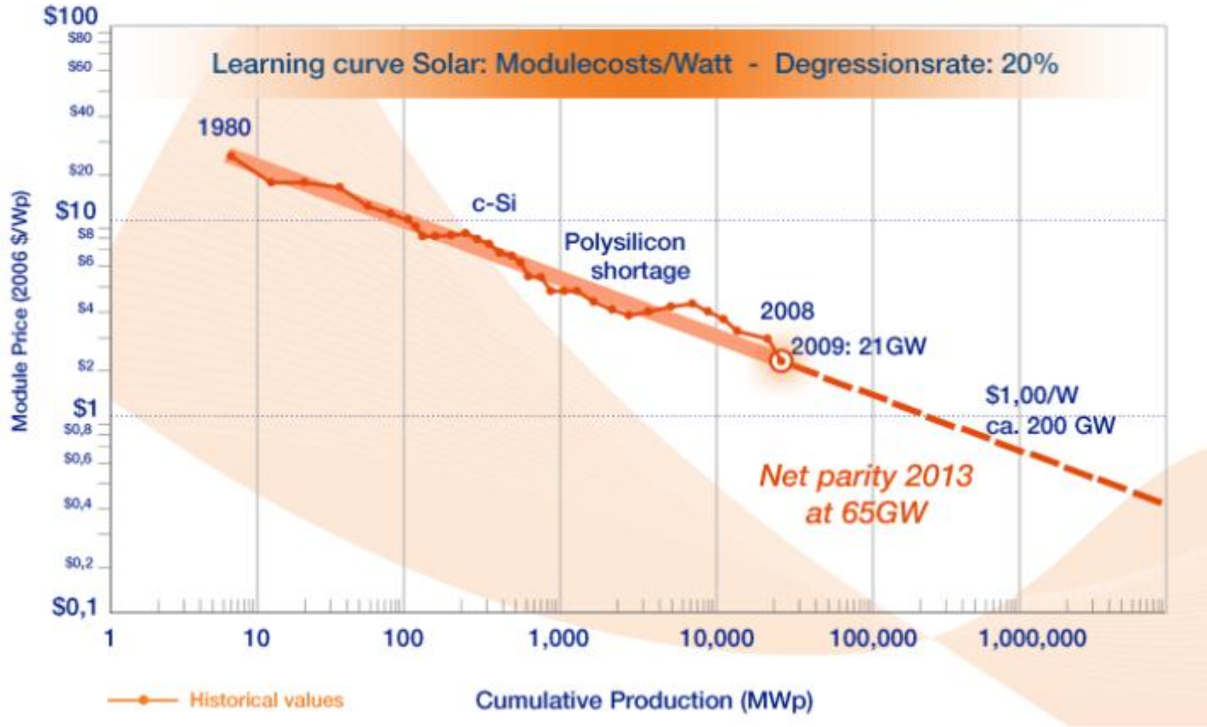


Figure 11.5: Development of costs for silicon modules from 1980 until 2009 (Sollarvalley, 2011b)

At first sight the trend shown in figure 11.5 seems to tell that the lowering of costs for silicon modules is going towards a minimum value, which in turns looks like the cost reduction potential for c-Si is largely used already. However, this seems not be true considering the amount of research still going in the field of increasing efficiency of c-Si cells and lowering manufacturing costs, as well as the previous figure which shows that such "flat" periods with little decrease occurred more than once and were followed subsequently by a decrease.

11.3 Knowledge diffusion

Knowledge diffusion with regard to silicon wafer solar cells takes place in Germany in a variety of ways. Examples are conferences such as the European Photovoltaic Solar Energy Conference (of which the 26th edition was held in Hamburg in September 2011) and the 1st international Silicon PV Conference, which was held in 2011 in Freiburg. At both these conferences quite a number of papers were presented on silicon wafer technology, although not all of them were of German origin as discussed earlier. Furthermore it can be questioned what the relevance is of the fact that such a conference took place within Germany, as both were international conferences. The answer to this could be that a conference located in Germany is more easily accessible (e.g. because of distance) to people from Germany than from other countries. However the second (2012) Silicon PV conference will take place in Belgium. Also the other editions of the European Photovoltaic Solar Energy Conference have been held in a variety of countries in the past, thus perhaps the best that can be said is that these conferences show that knowledge diffusion through conferences does take place in Germany, however not specifically and necessarily within the German technological innovation system. This is also the case with regards to for example workshops (e.g. on metallization for crystalline solar cells) which are held annually in a different location including, but not restricted to, Germany. Thus the national boundaries seem to have gotten less relevant in this regard, but they are a relevant contribution.

With regard to government funded joint research projects on silicon wafer technology, these are conducted by cooperating parties which can be firms and research institutes/universities. One of the main goals of the governmental funding of such projects is in fact to let different organizations interact and collaborate in order to transfer technology from the laboratory to industry. For example, in one of the governmental documents on funding of a silicon wafer research project it reads (BMU, 2009):

"The project itself proposes to produce cells in the laboratory with an efficiency of at least 21 %. The plans to transfer the concepts to areas of 10 x 10 cm2 and more – relevant to industrial applica tions – are intended to ensure that the technology can subsequently be used in industry."

Furthermore, in the governmental criteria for selecting projects it reads (BMU, 2009):

- *industry participation and a networking structure; preference is given to collaborative projects;*
- *development risk and time horizon for implementation;*
- *possibility of broad dissemination of the research findings, while taking into account the need to protect the findings through patents.*

Of these criteria for selecting projects, the first and third seem to be explicitly aimed towards knowledge diffusion. Within such funded projects, companies work together with each other and with research institutes. However, this cooperation is not restricted to German organizations. For example in a recent project one of the largest solar cell manufacturers in Germany, and in fact worldwide (Q-Cells), cooperated with the Eindhoven University of Technology (TUE) (BMU, 2009)

A further indication that knowledge diffusion has been a priority within the PV sector in Germany is the PV cluster that has formed in the former East-German states, which is the largest industrial PV cluster in the world (GTAI, 2011). The cluster was born out of the desire to secure the leading position of Germany in the field of development of technology, especially in the field of thin film PV, through clusters including players from research and industry. Such a cluster should subsequently facilitate transfer of knowledge as well as the quick application of R&D in industry (Bruns et al., 2011). Both silicon and thin film firms can be found in cluster form (BMWI, 2010). Also with regard to equipment suppliers there has been a cluster for both silicon wafer based and thin-film technologies (BMWI, 2010). In the PV industry overview 2011/2012 of the foreign trade and inward investment agency of the Federal Republic of Germany, it says:

"Close proximity to and cooperation with world class R&D institutions, universities, and leading material and equipment suppliers (covering everything from cell-related wet chemistry and vacuum deposition to automation and turnkey lines) helps manufacturers optimize production technologies and processes."

And:

"Company R&D centers not only profit from cluster knowledge transfer, but also from information sharing with other R&D centers and companies."

(GTAI, 2011).

An example of such a cluster is Sollar Valley in Saxony-Anhalt, Germany. It involves three German states, and focuses on coordinated R&D across the value chain (since the cluster comprises all of the production chain) in order to increase effiency and reduce component costs, countrywide integrated education such as the Solarvalley graduate school for PV, and finally the development of a countrywide network (Sollarvalley, 2011a). The focus on the last aim comes down to cluster management and supports the interaction of partners in the network in the form of, for example, improvement of internal communication, supporting spin-offs, expert discussions, political committees and press and PR work (Sollarvalley, 2011b).

The government itself is also actively engaged in knowledge diffusion through the German Federal Network Agency, which provides primary data on newly installed PV plants. This makes it more easy for service providers to identify their customer base and to test new concepts (i.e. services products) on a large scale. (GTAI, 2011).

Silicon

Thin film

An example of cooperation between organizations on R&D can be found in Würth Solar and ZSW, with regard to CIS cells. ZSW supports Würth Solar on scientific and technical issues, and also with the development of components (Powalla et al., 2005). This collaboration, which was crystallized in a pilot project, was particularly important since it helped the transfer of CIS technology from laboratory to industrial scale. After the collaboration with ZSW (Centre for Solar Energy and Hydrogen Research, Baden-Wurttemberg), Würth Solar in 2005 announced to pick up mass production of CIS cells.

Furthermore, around the beginning of this phase CIS-Sulfurcell GmbH started working with a deposition technology developed at the HMI (a research institute which did work on thin-film). Around 2004, they achieved efficiencies of 9.3% on an area of 17.1 cm^2, and their target was to scale up the size of the module towards over half a square meter by 2007 (Diehl et al., 2005). The actual knowledge diffusion here took place through a person, as Nikolaus Meyer who got a doctorate on CIS thin-film research at the HMI founded Sulfurcell, which was thus basically a spin-off of the HMI (Wengenmayr & Bührke, 2011). It could however be questioned why the entrepreneurial initiative came from *within* the research institute. The reason, according to the founder Nikolaus Meyer, was that there emerged no industrial interest as the path from laboratory to production plant seemed to long and the economic situation was weak (Wengenmayr & Bührke, 2011).

11.4 Guidance of search

In 2004, the Renewable Energy Sources Act (EEG) was amended (BMU, 2004). The amended act was different with respect to the previous one in a number of key aspects. Besides the raising of the tariffs as mentioned in the next function, with regards to the *Guidance of Search* function the most important amendment was that in the previous act the doubling of renewable energies in the power base from 2000 to 2010 was already established, however in the amended version this was laid out in more specific guiding principles: By 2010, renewables had to contribute at least for 12.5% to the electricity supply, and in 2020 the goal is 20%. Thus, this provided stakeholders with a concrete framework with regard to the diffusion of renewable energies. In 2006, a share of 11,6% was already reached (Wissing, 2006).

In general it can be said that the German government has had an extensive past of supporting renewable technologies. Also today, a sustainable energy supply is recognized as one of the governments' priorities, and innovation in renewable energy technologies are seen by the government as a key feature for a sustainable feature (BMWA, 2005):

"Today, Germany is faced with the task of pressing ahead with the transition to a sustainable energy supply. In addition to the basic conditions for an appropriate energy policy, this transition above all requires innovation and technical progress."

By 2050, the Federal Government aims for a 50% share of renewable energy in the total primary energy use. This translates, through the BMU department of the government, to funding for research on PV. PV, for the BMU, is one of the priorities for research. Within PV technologies, silicon wafer technologies receive the largest share of funding (51%) under the 5th energy research program (BMWA, 2005). The BMU has a specific vision on how it thinks silicon wafer technology should be approached. It sees reducing the materials used as one of the priorities (e.g. through new wafer sawing techniques or production of wafers without sawing), as well as improved manufacturing techniques to increase efficiency and new solar cell designs (BMWA, 2005).

Also the German silicon wafer industry has a clear vision of the future, as is evident from the roadmap, organized by the Crystalline Silicon Technology and Manufacturing (CTM) Group. The report was produced in 2010 by leading European silicon wafer cell manufacturers, module manufacturers and wafer suppliers, although by far most of the authors and firms involved were German. Requirements for c-Si cell manufacturing are mentioned in detail (e.g. on more effective use of material, or more advanced processes). This is necessary, for example, because other supporting technologies need to be aligned to the new developments regarding silicon wafer solar cells. Thus the road-map seeks to guide new developments towards a common application. Furthermore, the roadmap states that in order for PV to reach the overall cost target, the module efficiency must go up and the manufacturing costs must go down significantly. There seems to be little focus however on new cell concepts. (ITRPV, 2011). This could be due to the assumption that a reduction of manufacturing costs per Wp is primarily depending on a reduction in manufacturing costs per wafer, cell and module, more so than on increasing efficiency (ITRPV, 2011).

Furthermore, the PV industry expects to be providing for 12% of the energy in Europe by 2020, compared to the less than 1% that is covered in Germany at present (Sittinger et al., 2010)

There are also expectations for further efficiency increases for both crystalline silicon en thin-film modules. These expectations are a main driver for further research, as naturally research on efficiency is done if there are good prospects of increases in efficiency, and increase in efficiency leads to cost reductions per kW. For example, in the work of Wand & Leuthold (2011), we find a future estimate of the cost development of crystalline silicon and thin film modules as shown in figure 11.6.

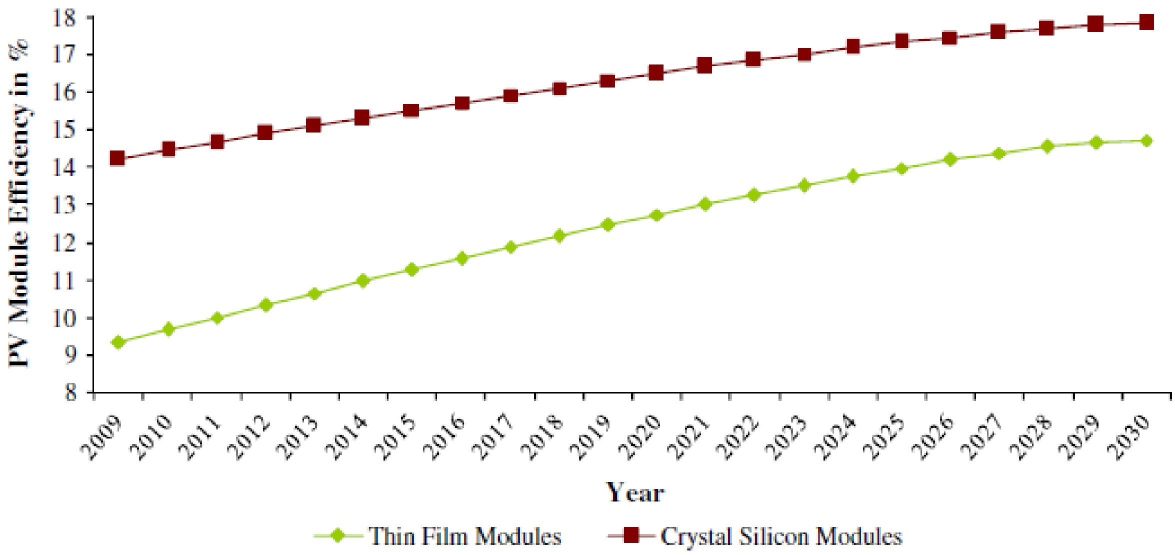


Figure 11.6: Future development of estimated module efficiencies for thin film and crystalline silicon modules (Wand & Leuthold, 2011).

It can be seen that according to Wand & Leuthold, (2011), the difference in efficiencies between crystalline silicon and thin film silicon modules will decrease in the future as the two lines converge.

In 2010, the German National Renewable Energy Action Plan was published which sets a target of 18% for the contribution of renewables to meet the gross domestic energy consumption for the year 2020 (Wissing, 2011).

11.5 Market formation

The 100,000 roofs program ended in 2003, while the amendment of the EEG (which was needed in order to make PV more attractive without the 100,000 roofs program) was planned around mid-2004 (Bruns et al., 2011). This gap period of about 6 months without support could turn out to be problematic for the PV industry, which was not self-supporting. Therefore an Interim Act on Photovoltaic Energy was adopted in December 2003 (and came into effect January 2004) in order to prevent a setback of the PV sector in this period, which was more than half a year before the amendment of the EEG (Bruns et al., 2011). The focus on the act was the compensation conditions for PV under the EEG and it was meant as a compensation for the end of the reduction of interest rates present under the 100,000 roofs program (Bruns et al., 2011). In this Interim Act new compensation rates for PV generated electricity fed into the grid were stipulated, which were later also incorporated into the amended EEG act in August 2004 (Bruns et al., 2011). Whereas at first the compensation for PV systems on buildings was 45.7 cents/kWh, this increased with 11.7 cents/kWh if the capacity of the system was up to 30 kW, 8.9 cents/kWh if the capacity was between 30 kW and 100kW, and 8.3 cents/kWh for systems exceeding 100kW (Bruns et al., 2011). Also a 5 cent/kWh bonus was introduced for systems integrated into building facades (Bruns et al., 2011). The development of the compensation rates for PV rooftop systems up to 30 kW under the StrEG and EEG over the years is shown in table 11.4.

		1991	1995	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Rooftop systems up to 30 kW		StrEG			EEG 2000				EEG 2004					EEG 2009	
Nominal compensation payment	Cent/ kWh	8.5	8.8	8.4	50.6	50.6	48.1	45.7	57.4	54.5	51.8	49.2	46.8	43.0	39.6
Compensation payment in 2009 prices		11.9	11.0	10.0	59.3	58.1	54.5	51.2	63.3	59.2	55.4	51.4	47.7	43.0	38.9

Table 11.4: Development of compensation rates under the StrEG and EEG acts (Bruns et al., 2011)

These features of the Interim Act which closed the gap between the 100,000 roofs program and the amendment of the EEG were incorporated into the amended EEG in August 2004 (Bruns et al., 2011). After the EEG was amended, the German PV market continued to grow (Bruns et al., 2011). Since the production capacity in Germany could not meet all the increasing demand, Germany increasingly became an importer of for international manufacturers, which also motivated German manufacturers to increase their production; however still the sales were restricted by the limited supply (Bruns et al., 2011). More new systems were installed each year compared to the period before the EEG amendment was adopted, which can be seen in table 11.5. As can be seen in table 6, in 2008 again the EEG was amended, this time by increasing the price reductions (9% after 2011).

The EEG is still the main driver for the PV market today (Wissing, 2011).

		1990	1991	1992	1993	1994	1995	1996	1997	1998
Installed capacity (MWp)		1	2	3	5	6	8	11	18	23
New installations (MWp)			1	1	2	1	2	3	7	5
Growth on previous year			100%	50%	67%	20%	33%	38%	64%	28%
Market stimulated by:			1,000 Roofs Program				Municipal cost-covering compensation			
	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Installed capacity (MWp)	32	76	186	296	439	1074	1980	2812	3977	5877
New installations (MWp)	9	44	110	110	143	635	906	832	1165	1900
Growth on previous year	39%	138%	145%	59%	48%	145%	84%	42%	41%	48%
Market stimulated by:	100,000 Roofs program, Interim act on Photovoltaic energy					EEG 2004				

Table 11.5: Installed capacity of PV systems in Germany from1990 to 2008 under the different policy programs (Bruns et al., 2011).

Germany has the largest installed capacity of solar cells in the world (17,3 GWp), as well as the largest amount of new installed capacity by the end of 2010 (7,4 GWp) (GTAI, 2011). In 2009, it appeared that 53 percent of total global installations was installed in Germany (Chemistryworld, 2010). The take-off for the German solar market started in 2000, when solar electricity became a viable option to invest in for the first time. This was due to a combination of the revised Feed-in law and the 100.000 roofs program. Worldwide, the market share of silicon wafer solar cells is by far the largest of all PV technologies. Specific information for Germany in this regard was difficult to find, however it can safely be assumed that this also holds for Germany, considering the relatively long establishment of silicon wafer technology in Germany, and considering the fact that Germany itself makes up a large part of the worldwide PV market (Germany is home to almost half of all operating solar modules worldwide (GTAI, 2011). Silicon solar cells have been applied in different applications, such as on roofs or in large solar power plants. The residential sector has by far the largest amount of PV installed (about 85%), whereas field installations make up the rest of the capacity (GTAI, 2011). Although silicon wafer solar cells have more efficiency, they are also more expensive than the most common thin-film solar cells. This means that there exists a trade-off when designing a solar system; silicon wafer solar cells will generate more electricity on the same surface as thin-film solar cells, and thus they will need less area. Thin-film cells, however, are cheaper, but they generate less electricity on the same area compared to silicon wafer cells, and thus they need more area to generate that same amount. Although no general conclusion can be inferred from this (i.e. what solar cell is used in what type of application), in general it can be seen that thin-film solar cells increase in attractiveness at large areas (at the scale of ground mounted systems/solar power plants), and that at the scale of roof systems silicon wafer cells are by far most used (authors analysis). Nonetheless, in Germany's largest solar power plants, around 60% utilize silicon wafer cells, which is still the majority, but a considerably lower share than in smaller applications.

11.6 Resources mobilization

Human resources

With regard to human resources, a number of aspects in this regard can be covered. In a general sense (I.e. not specific to PV), labor quality in Germany is among the best in the world; productivity figures in manufacturing by far top those in China and Japan and are comparative to those in the US (Suzuki, 2007). Also, Germany has a large PhD output in natural sciences, only being second to the US (Moguérou, 2005). In figure 11.5, the PhD output for natural sciences and engineering up till 2002 is shown (Moguérou, 2005).

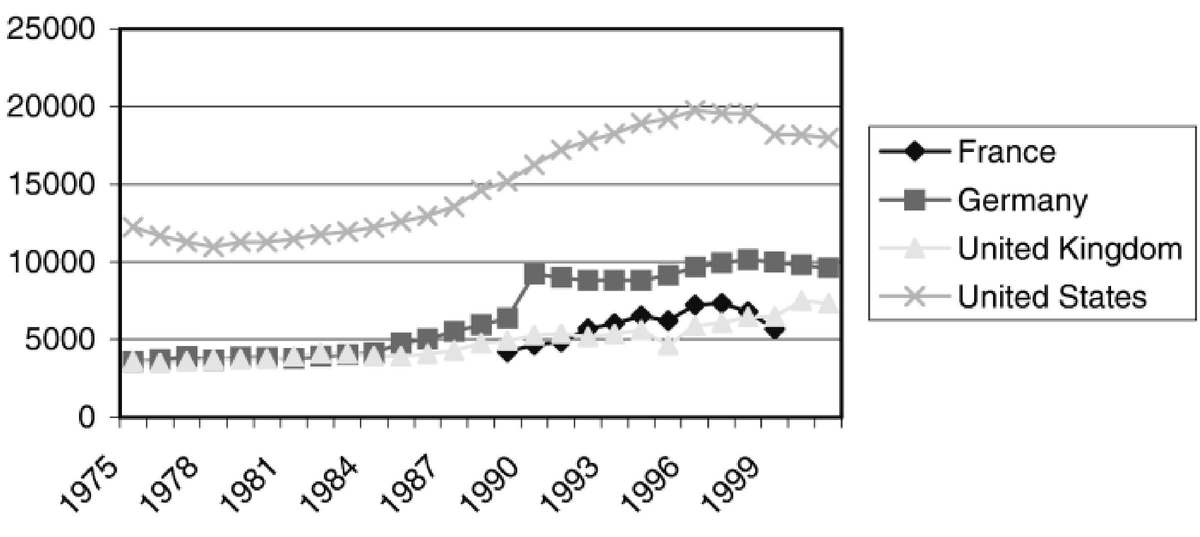


Figure 11.7: Number of PhD graduates in natural sciences and engineering (Moguérou, 2005)

Furthermore, specialized labor is available from the semiconductor industry, an industry that is highly related. An example is 'Silicon Saxony', which is a registered industry association with almost 300 firms that operate in the microelectronics industry or a related industry in Saxony, Germany, employing about 40,000 people. This includes German PV, such as the firm Solarworld. Furthermore, the PV industry in Germany is very concentrated into clusters, which allows for specialized training facilities as well as the pooling of the labor market. An example of this can be found in Erfurt (in Saxony), where a vocational training site is built which provides space for 351 students in the field of PV : The "Kompetenzzentrum für Hochtechnologie und Solarwirtschaft" (Maruschke, 2009). Furthermore, in Germany more than 100 bachelor and nearly 80 master programs have a focus on renewables, and 20 of these programs focus almost exclusively on PV, such as the bachelor program "Solartechnik" at FH Anhalt (WILA, 2009).

It appears that at in the beginning of this phase there was a shortage on suitable educational material (FVEE, 2004). The output of the c-Si PV sector at the moment does not seem to point to a problem in human resources. In Germany, about more than 240 university degree courses focus on PV and other renewable technologies. Furthermore, close cooperation between the microelectronics and semiconductor industry and the PV industry lead to an employable workforce (GTAI, 2011). However, a shortage of qualified staff is also reported on all levels (e.g. engineers and researchers), which indicates a need for capacity building (PV Employment, 2009). And although there are related university courses, the number of students is still limited. Furthermore, a lack of traditional dual training courses for solar techniques led Q-Cells, one of the world leading PV companies, to report a lack of suitable applicants for open vacancies in recent years (RESProject, 2011).

Materials

The high demand sparked by the 100,000 roofs program and the EEG of course was positive for the diffusion of PV, however it also had a negative impact. High demand and a shortage of silicon as a raw material caused the prices of modules to rise. In 2004, demand for silicon exceeded supply and in 2005 the supply was 30% less than the demand (WikiInvest, 2011). Due to this, prices rose from $24 in 2004 to $450 per kg in 2008 for solar-grade polysilicon (WikiInvest, 2011). Furthermore, the semiconductor industry which also makes use of silicon could outbid the solar industry due to the fact that silicon makes up a much smaller portion of their production costs (Gartner, 2005). At present however, the silicon shortage has ended due to new added production capacity, causing polysilicon prices to drop sharply (Roca & Sills, 2011).

Space

An interesting aspects of resources in the case of PV is the space it needs. Without area that can be covered with PV modules, there can be no PV electricity generation. Increasingly, a shortage of roofs and sites suitable for PV modules has been reported by project planners (Bruns et al., 2011). Furthermore, suitable sites and roofs that can be leased are becoming more and more expensive (Bruns et al., 2011).

Financing

Although the 100,000 roofs program had ended by now, new funding came in the form of an amendment to the EEG which went in to effect in 2004 as mentioned earlier. Under this new amendment the remuneration rose by 11.7 cents to 57.4 cents/kWh for installation on buildings with a maximum capacity of 30kW, for an output over 30kW up to 100kW it rose by 8.9 cents/kWh and for systems with a larger capacity with 8.3 cents/kWh. Furthermore, an extra bonus was in place of 5 cents/kWh for facade mounted installations (BMU, 2004).

The focus of BMU funding for R&D in PV approved in 2010 is on silicon wafer technology (51%). However, R&D support seems to be small relatively to the deployment support (Grau et al., 2011). Currently, deployment support (i.e. the feed-in tariff) is worth 4,720 million euro's, compared to 650 million investment support for manufacturing plants and 60 million R&D support (Grau et al., 2011). Over the years the public R&D support for PV seems to be decreasing (Breyer et al., 2010), leading, the PV industry and the research sector to appeal for an increase in R&D budget for PV (Breyer et al., 2011).

In 2008, 2,183 million has been invested by the German industry in the construction, expansion and modernization of solar production factories. (Grau et al., 2011). Industrial R&D investments have been 163 million in 2008, however this is a general figure not specific to a PV technology. More specific information could be the fact that the German PV industry spends 4,2% of sales on R&D. Considering the fact that the silicon wafer market is still by far the largest specific PV technology market in Germany, probably most of this 4,2% is to be attributed to silicon wafer R&D in industry in absolute terms (Breyer et al., 2010). This is because even if the R&D/sales percentage of the thin-film sector were to be significantly higher (e.g. 10%) than that of the c-Si sector, this percentage would drop massively if the total R&D investment in the thin-film sector is divided by the total sales of the PV market (c-Si plus thin-film sales). This implies that the c-Si sector must have made a significant contribution to this percentage. This is, however, on the assumption that most of the income from sales in the c-Si sector is retained within c-Si R&D. This assumption can be inaccurate in the case of large firms that do both c-Si and thin-film related research (thus enabling these firms to get income through c-Si sales, and then invest it in thin-film research).

Thin Film

CIS cells are cells that need significantly less semiconductor material in comparison with silicon solar cells. The downside, however, is that the chemical elements needed for this type of cell are relatively rare and used in other mass products as well (for example, Indium is used in LCD screens). Thus, if the demand for the involved scarce materials would rise, the price of these materials and thus the price of CIS solar cells would also increase (Wirtz & Janssen, 2010). Nonetheless, Sulfurcell was able to raise $25.6 million on equity funding in 2011 in order to introduce its CIS technology to the market (Nusca, 2011).

11.7 Advocacy coalitions

At present, renewable energy supporters have strong influence, and the important role played by advocacy coalitions has been evident in the past, for example EUROSOLAR in advocating the 100,000 roofs program. At present, an important contributor is the German Solar Industry Association (Bosman, 2012). One of their most important activities is political consulting, which basically implies systematically lobbying for investment security and suitable market incentive programs, and creating consensus among politicians for the need for PV energy in the future, thereby stressing the need for the expansion of the PV market (BSW, 2012). These activities are also on an international level, as the BSW is a member of the European PV Industry Association (EPIA), an organization that represents PV industry on a European level. An example of an achievement is the initiation (2007 first event) of the “Week of the Sun”, where more than 3000 events related to solar energy take place across Germany. Besides being supported by industry and BSW, it also receives support from the German Federal Ministry of Environment (Solardays, 2012). The BSW played an especially important role in around 2009/2010, when the new Merkel government was installed, which intended to revise the support for solar energy within the EEG law (Bosman, 2012). As the number of installations had been rising steadily, the costs of support for the solar systems also grew, which motivated movements to limit these costs. The BSW then initiated a large campaign, involving solar industry companies going on strike and nationwide advertisements being spread to increase awareness on the proposed cutbacks (Bosman, 2012). Although the final result of this struggle was a compromise, it was largely successful due to the fact that the cap on installations had been removed, and the new installed capacity in 2011 amounted to a record of 7,500 MW. This clearly indicates the strength of the advocacy coalition (Bosman, 2012).

Another example of advocacy coalition activity in this period are the efforts against the proposed harmonization of the European support scheme for renewables. It was feared that such a harmonization would effectively end the successful EEG law, and the German government agreed (Bosman, 2012).

Also the general public in Germany agrees on the importance of an energy transition from dependence on Nuclear and fossil energy towards renewable energy sources, and is even willing to financially support this (which is already happening), and issues regarding energy household are also influencing the voting behavior of the public (Bosman, 2012).

There is also support from research institutions, which can bring their expertise into the debate. For example, 7 well known research institutions (including the Fraunhofer Institute which is a leading research institute) produced a report (“Energy Concept 2050 for Germany with an European and Global perspective”) showing the feasibility on the long run of an exclusively renewable energy household (Bosman, 2012).

Furthermore, there was broad support from the government, as within the government consensus exists on a general level with regard to energy policy. Even the conservative government (the opposition is yet more progressive) supports the energy transition and the phase out for nuclear power (which was related to the nuclear disaster in Japan). As Rösler, Economics Minister and one of the most conservative players, puts it: 'Our goal now is to exit from nuclear power faster than previously planned.’ 'The pace is crucially dependent on how fast we can develop alternative sources of energy. The decision to exit from nuclear power was not satisfying in itself; we therefore initiated or changed 16 laws inorder to also safeguard our entrance into renewable energies and ensure a reliable energy supply.' (Bosman, 2012).

This shows that renewable energies enjoyed broad support from public and government, which was of course necessary as the public had to invest in these systems for a significant part, while policy makers had to support financial market incentives.

11.8 Conclusion

As the market incentives provided made PV an economic option for electricity generation, the market grew further and the number of companies increased. Whereas in early periods it was mainly large existing firms that extended their business into PV, now more and more companies focusing solely on PV entered the market, which shows a maturing development of the market. Nonetheless, at present it can be questioned what the need is of German manufacturers, given the fact that PV modules can be easily imported from foreign countries (e.g. Asian) in todays globalized market. This is in fact done at present, although most modules are German. It seems then that the increasing number of German manufacturers in the German market is a "symptom" of a growing market, rather than a key facilitator of diffusion.

Research was continuing and c-Si silicon remained the largest priority within the 5th federal energy research program. However, early in this period the amount of papers on organic PV from German origin surpassed the amount of German papers on other PV technologies. Thus the federal government did allocate funding (through the BMBF) in cooperation with industry, which contributed much more. This, however, does not represent a comprehensive view of the distribution of R&D funding on PV technologies, since the large growth in the amount of papers on OPV are more oriented towards basic research funded partly with public funding, more suited for public publication, whereas more mature technologies have less basic R&D and more industrial R&D. Thus we can see that all PV technologies are improving, and that OPV is making itself ready within Germany for suitability for the market. However, further research on even the more mature technologies is still necessary, as cost reductions are needed in order to make PV competitive on the grid. It is evident that the German Federal Government chose to partly give in to the lock-in situation that developed for c-Si silicon with regard to R&D funding, given the fact that c-Si material is not the ideal material for PV but nonetheless the most entrenched technology in the PV market. But with the research being done on other PV technologies also, the German federal government nevertheless keeps a diversified portfolio, which positions it well for future developments, whatever PV technology may develop to become dominant (if it all, since coexistence is also possible).

An essential feature that could be seen in this period of German policy with regard to PV was its consistency. For example, after the ending of the 100,000 roofs program, the EEG was amended so that PV would remain a viable economic option for investors. According to Vasseur & Kemp (2011), this has been one of the main reasons behind the growth of the PV market in Germany. Furthermore, the restriction to up to 100kWp was lifted for PV systems after 2004, which now provided motivation for installation of larger systems, which made up 70% of installed capacity in 2009 and 40% in 2005 (Vasseur & Kemp, 2011). With regard to resources, it can be said that there has been an adequate mobilization in all regards, although materials posed a problem early in this period which was later on resolved. It is not surprising that a new emerging market, experiencing a boom in development, with its own material requirements, needs time to adapt to a booming market in terms of raw materials supply (i.e. in the case of silicon). This is especially true given the fact that silicon supply was initially geared towards the semiconductor industry. This shortage nonetheless did, on hindsight, not really affect the diffusion of PV, and it had a positive side effect namely being an extra motivation for research into different technologies. Germany in this regard is well placed also today with a diversified portfolio of PV technologies in R&D and production. An increasing scarce resource however could be space for locating the PV modules, as has been pointed out in the sixth function, which was in fact already reported as an increasing difficulty. This could lead to higher prices per m^2, which necessitates higher efficiencies to generate the same amount of electricity on smaller areas. However higher efficiencies within a PV technology usually imply higher costs. In order to calculate the most cost effective viable option, different factors must be taken into consideration, as well as their dynamics. For example, the area related costs should be weighed with the costs of the module itself, and the electricity supply requirements (e.g. how much) should be taken as boundary condition. With knowledge of such costs, it can then be calculated what kind of PV module is most economical. Thus the spread of PV technology is not without its problems, and this will also need the focus of the advocacy coalitions. The advocacy coalitions in Germany had broad support from public and government, which was essential in securing a consistent policy of financial incentives for PV technology. The advocacy coalitions had been primarily engaged in removing institutional obstacles and lobbying for financial incentives, however it seems that with the further spread of technology the advocacy coalitions will increasingly have to busy themselves with dealing with (essentially) practical obstacles that are not in essence institutional (e.g. creating or securing space for PV applications).

12. Competition analysis

12.1 Function 1: Entrepreneurial activities

Early on it had become clear that already c-Si solar cells had an advantage over thin-film cells (of which a-Si was closed to commercialization). The basic material for c-Si cells, namely crystalline silicon, was already used in the semiconductor industry and was thus available in sufficiently pure form. It was therefore not surprising that firms such as Siemens and AEG Telefunken, both active in the semiconductor industry already before this period, were trying to exploit c-Si for a new promising application such as solar cells. Thus from an industry perspective, thin film solar cells at this point were already lagging behind in terms of commercial exploitation.

In the next period, interest in a-Si thin film technology increased, and thus c-Si had to compete for this entrepreneurial interest with a-Si. This is indicated by Siemens now also focusing on a-Si technology (whereas formerly its only field was in c-Si PV), and MBB investing in a a-Si production plant. It is likely that there was not yet a clear vision of what would become the extremely dominant technology in later periods, namely c-Si. Would this have been the case, it could be expected that the active firms would want to capitalize on the growth of the c-Si PV market by focusing its resources early on. Especially given the fact that c-Si modules are expected to stay dominant for quite a while even after today. Thus on hindsight, there was enough time and market growth in Germany for a firm to prepare for and capitalize on the growth of the c-Si PV market. This tells us that the future distribution of market size among the different PV technologies was not yet so clear, which is not surprising if we consider that at this time a-Si PV technology had a market share of 40%, which is much more than today.

It took a while for further relevant changes to develop due to the stagnation that resulted in the third period. In the meanwhile, it seemed that worldwide production figure for a-Si modules were now dropping (from around 1991), while overall c-Si module production was rising (Menanteau, 2000). Around 1998, a-Si cells still had a comparable price to that of c-Si cells, although manufacturing processes were already well understood and mastered for some time at this point (Menanteau, 2000). This was due to the insufficient demand, which caused a lack in economies of scale. It could be questioned under what function this should come. Clearly, it has to do with competition between PV technologies (i.e. c-Si and a-Si PV), and it has do to with entrepreneurial activities as well. After all, economies of scale imply larger scale production, and larger scale production can only emerge from entrepreneurial activity. Nonetheless, these entrepreneurial activities with regard to TF PV now more and more were becoming related to other factors, such as the market and the demand. In other words, there could be no entrepreneurial activities for a certain PV technology leading to large scale production if there was not enough (anticipated) demand. In my view this relates to , from an industrial TF PV perspective, a hampering transition from pilot activities and/or a small niche market (e.g. space technology) towards wide spread market diffusion. Whereas before PV diffusion seemed to be driven by technology push (e.g. consider the technological niches such as space technology early on), now a situation was created where the PV sector was beyond its initial stages (e.g. in the space sector), and was ready to grow, but the next stages of development were slow in coming and thus the PV sector found itself somewhere in between. Expectations early on had triggered investments in a-Si thin film cells, but further technological developments lagged behind and a-Si was still less attractive than c-Si PV. Between 1994 and 1998, Siemens stopped its activities in the field of a-Si, although both Siemens and ASE had both established a broad range of PV technologies such as a-Si, c-Si and CIS (Bruns et al., 2011). Siemens went further into the field of CIS PV (Bruns et al., 2011). ASE however continued its activities in the field of a-Si, as well as c-Si. In the meantime, it seems that the 1000 roofs program (which ended in 1993) and anticipation on international developments gave rise to expectations (Bruns et al., 2011), also of a growing grid connected market on the roofs, for which c-Si PV was most suitable. Thus, after the stagnation of the PV industry, between 1994 and 1999 a number of new c-Si PV firms entered the market, such as Ersol, Solar Fabrik, Solon and SolarWorld.

However, can these events in the phase before the boom be called competition? Competition by definition arises when two or more entities strive to achieve a goal that cannot be shared, or which is desired to have alone without sharing and cooperation. This is not totally applicable to entrepreneurial activities in Germany, as it has been pointed out that firms could have multiple PV technologies in their portfolio. But in another sense it was competition, as c-Si PV attracted more entrepreneurial interest than other thin-film technologies (even a-Si, which at first induced high expectations) which was evident in the period 1994-1998, due to the anticipated emergence of a market where a-Si cells would simply be inferior to c-Si cells, i.e. in the grid connected market on the roofs. Although attempts were made to put a-Si PV forward as a more attractive option for building integrated PV (BIPV), in practice this was not realistic from an economic perspective with regard to large scale diffusion of PV that was about to come. Thus rightly so, c-Si PV got more entrepreneurial attention. But even if a-Si had gotten more entrepreneurial attention, the market developments would not have been in favor of a-Si. Thus it cannot be said that a-Si here was striving for entrepreneurial interest (in a passive sense of course), as that was not the main concern. The main issue was the direction in which the market was developing (e.g. towards grid connected systems where c-Si was more attractive), and the weight of factors causing competition shifted from entrepreneurial activities (early on) to demand and market driven developments in subsequent periods.

Nonetheless, weight shifted back partly to the entrepreneurial side as is evidenced by entrepreneurial activities in the field of TF PV later on, such as the establishment of Würth Solar in 1999 and Sulfurcell some years later. This was the result from R&D developments in research institutes which has been described earlier in this thesis. These developments led to expectations among certain parties that decided to invest in CIS technology, although diffusion in the market was not yet at hand. However, as the incentive programs for PV (e.g. 100,000 roofs program, EEG) were implemented, the c-Si PV market grew immensely as most installed installations were with c-Si cells. This made the thin film market increasingly small in a relative sense, and it resulted in much entrepreneurial activity in the c-Si sector and little in the TF sector, as evidenced by the fact that by 1999 only 3 companies had production lines in the TF sector, whereas in the c-Si sector this was much more. However within a relatively short time frame, namely in the last period, quite a number of TF companies emerged in the field of a-Si and CIS.

Nonetheless, if we compare the production capacities in the c-Si and TF sector it is still clear that the c-Si much bigger. There are a few companies (e.g. Schott Solar and Ersol Solar) that are active in both c-Si and a-Si technology, but also their c-Si production is much more that their TF production. With regard to the other companies, these are specialized companies in the field of CIS and a-Si and there is not necessarily competition in the sense of entrepreneurial activity, as the different entrepreneurial activities can coexist.

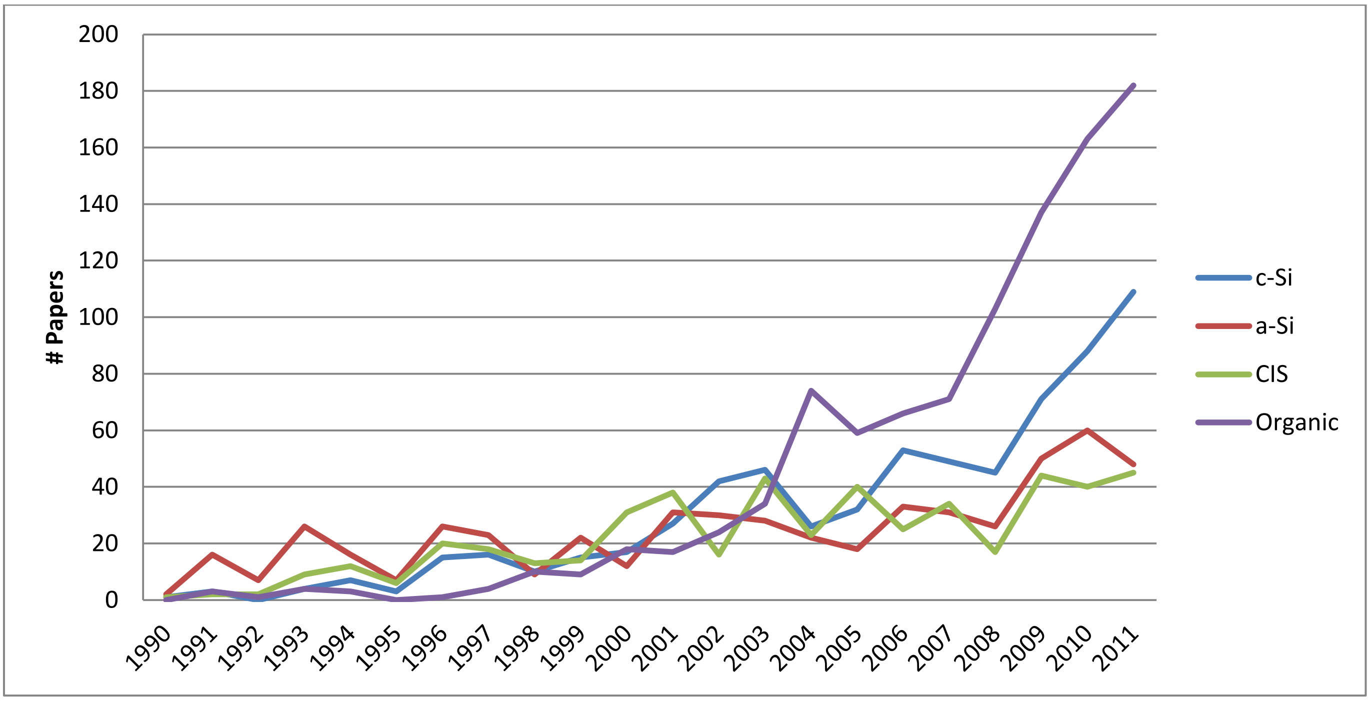
It is difficult to assess whether or not the previous can be described as competition. However, entrepreneurial activities *can* coexist for different technologies, as it is something companies can initiate whenever they want to, for any technology they want to (of course now we do not regard their success in this). This is in stark contrast with, for example, market share which cannot be created on demand but is rather a result of certain processes.

12.2 Function 2: Knowledge development

With regard to learning by searching in the first period from the perspective of industry and research institutions, it is evident that there was less bias here towards c-Si technology. The different PV technologies had to compete for resources and c-Si solar cells definitely had to compete in terms of support for R&D with other thin film technologies, which was caused by expectations surrounding the other thin film technologies, of which a-Si at this point induced the highest expectations. This points to the interesting fact that already at this point in time there was the vision that c-Si technology was not the optimal technological configuration and that it would be replaced by thin film technology in the future. However, the thin film technologies were also competing amongst themselves for attention from research institutes, of course not in an active, but in a passive sense. But with regard to learning by using there was a bias towards c-Si technology, not because of choice but more because of the state of affairs at that time. C-Si cells were closer to commercialization and were more suitable for testing in demonstration projects, which happened at this time. This caused experience to be gained with regard to electricity generation of c-Si modules, along with knowledge about long term reliability, maintenance etc. This further increased the strong position of c-Si modules as it started to become a technology with a reference in the desired fields of application, in contrast with the other thin-film technologies.

In the second period, while the amount of scientific papers from German origin on c-Si modules was at a constant low in this period, the amount of papers on a-Si technology gradually increased, and it seemed that a-Si was being more and more considered as a viable option for large scale terrestrial application. The increasing industrial interest in the a-Si technology was also reflected in increased industry R&D. Also the CIS technology was being researched, although it doesn't seem that a lot of growth took place in this period in terms of papers. On the other hand however, more and more experience was being gained with the application of c-Si technology. Data from demonstrating projects was now becoming available and learning took place in different parts of the value chain. This was in contrast with thin film cells, where no demonstration projects seemed to have taken place and learning by using did not yet take place. This can be explained by the fact that "PV energy" at this point in time was still at an infancy stage with regard to market formation, and thus the focus was more on doing something new with what is at this moment the most suitable technology than on what type of PV technology should be used. Thus thin film PV cells were, with regards to using them with a vision towards large scale terrestrial application, on the background and c-Si took the attention. This implied that c-Si were given a further advantage in terms of market formation. If thin films had to take a relevant position in the market earlier on, as was clearly envisioned judging from the published papers on TF PV in this period, on hind sight demonstration programs should have been initiated, or forced, already in this period in order to balance the learning by using between the different PV technologies. This, of course, would not directly increase efficiencies of thin film PV technologies or decrease their costs, but it could lead to a situation where a market for thin film would open up more easily (due to the existence of reference applications), which in turn could lead to entrepreneurial interest and more R&D for thin film PV.

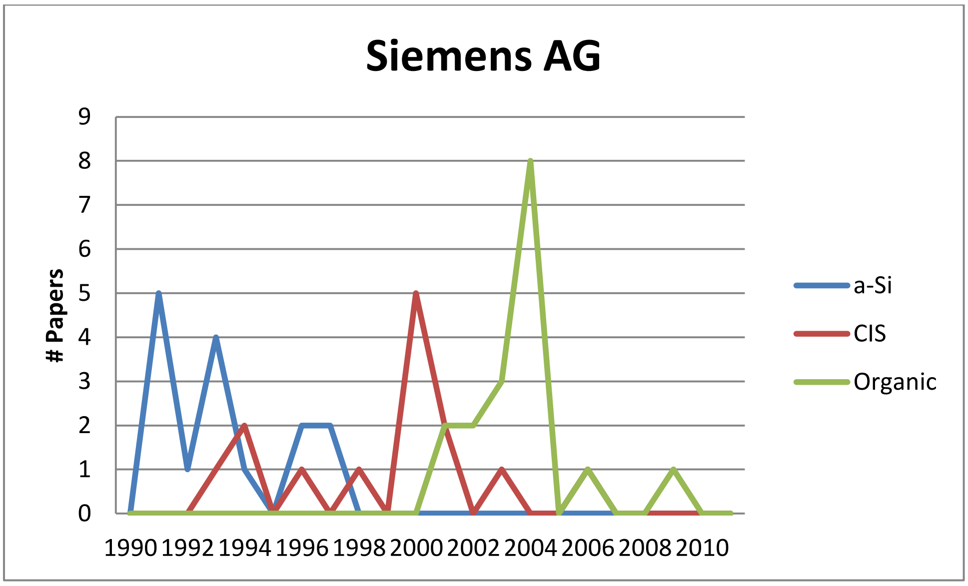
Nonetheless, a broad scope was present with regard to R&D on PV technologies in research institutes, as well as in industry (although industry was still small), and thus there was competition for research funding as all had to be funded from a limited pool of money. However, this competition was not of such a nature that an absolute increase of research into one PV technology meant an absolute decrease of the research into another PV technology, which is illustrated in figure 12.1. It can be clearly seen that especially in the period before the boom (I.e. before 1998), the development of the number of German papers on the different PV technologies show a synchronous development with ups and downs at approximately the same time. This is opposite of the hypothetical case where an increase in research into one PV technology would go together with a decrease of R&D into another PV technology. Thus this shows that the competition between the technologies in the sense of learning by searching was not to the level of extinction of other technologies, but merely in a proportional sense where each technology had its rather constant share of funding in this pre-boom period (which is indicated by the same hierarchical order of a-Si highest, then CIS,then c-Si and the organic PV).



Figuur 12.1: The development of the number of papers from German origin on different PV technologies over time (taken from data on Scopus)

This order changed however after the boom, as can be seen in figure 12.1. Whereas the development of the number of papers was rather synchronized at first, after 1998 the synchronous nature apparently diminishes (although is not totally lost) and the number of papers on a-Si for the first time becomes lower than the amount of papers on other PV technology. Emerging from this rather chaotic period, which lasted between 1998 and approximately 2004, is a new hierarchy where organic PV, from being lowest in the pre-boom period, now is at the top of the number of German PV papers, followed by c-Si and then in alternation a-Si and CIS. This shows that expectations (e.g. market expectations) have changed drastically after the boom, and the scales of competition changed with this. Some synchronization in the development of the number of papers on the different PV technologies emerged in the present period, with a different hierarchy as mentioned, showing that after the chaotic transition period (1998-2004) organic and c-Si PV technology were better off in the in the competition for R&D attention from research institutes than other PV technologies. Organic PV and c-Si were not competing directly for the resources of the same government department, since c-Si PV was sponsored by BMF and organic PV by BMBF. C-Si was competing directly with other TF technologies, and c-Si did get the majority of the BMU funding. Thus the direct competition between organic PV on the one hand and the other PV technologies on the other seemed to be more on the level of the research institutions rather than on the level of the government.

Also in industry there seemed some competition between the technologies, although at first not so many firms were active. An example can be found in Siemens, of which the amount of published papers on different PV technologies is given in figure 12.2.



Figuur 12.2: Amount of papers on different PV technologies from Siemens.

It can be seen that when a-Si technology entirely vanished from Siemens research, the amount of CIS PV papers peaked, and when CIS became much less, the papers on organic PV became much more.

From the angle of learning by doing, it is obvious that for c-Si PV much more products have been produced historically and also at present. This can be used as an indication that more learning by doing took place for c-Si PV than for other TF PV technologies. However, it cannot be said that the different PV technologies here were competing directly, since in theory the goal of learning by doing can be achieved for different technologies simultaneously without affecting other PV technologies. For example, consider that companies A, B and C could produce a certain quantity X of c-Si technology, whereas companies D and E could produce a certain quantity Y of CIS technology. The more production takes place, the more learning by doing is expected to take place. X and Y are in principle independent outputs (and thus the learning by doing from this production also) and a growth of X does not impede a growth of Y and vice versa. In other words, the sum of X and Y is not a fixed constant where X+Y=c (constant), and thus X=c-Y and Y=c-X are not applicable relations in this case. However, on practical grounds there are, of course, constraints such as the market sizes for the different PV technologies which are bound to influence production figures. For example it is beyond doubt that a 90% market share for c-Si cells will trigger much more production in the c-Si PV sector, compared to the 10% TF PV market size. However, this is not competition coming from learning by doing, but competition in market size.

12.3 Function 3: Knowledge diffusion

With regard to knowledge diffusion, it doesn't seem that relevant competition took place in the sense that more knowledge diffusion with regard to one PV tech hampered the knowledge diffusion of another PV technology. Nevertheless, there are some examples where competition might have played a small role. For example, on PV conferences usually topics relating to different PV technologies are presented, although some PV technologies prove to be dominant in terms of the number of presentations over others. Thus within the limited time to present in such a conference, a choice of topic must be made that can be presented. However, looking at indicators such as cooperation between R&D institutions, no reason was found why cooperation on one PV topic should exclude or diminish cooperation on another PV topic. Research institutions were found to collaborate on different PV technologies simultaneously, and the same holds for collaboration between industry and R&D institutions.

An interesting thing to mention is that instead of competition, it is likely that mutual benefit exists between the PV technologies in this function. This is due to the fact that PV R&D sections in R&D institutions establish connections with other such sections on the basis of research into a particular technology, but can also exploit these established connections and networks with regard to other technologies, as has been indicated by the fact that research institutions cooperate on multiple PV technologies simultaneously.

12.4 Function 4: Guidance of search

A key development early on relating to competition between PV technologies that was pointed out is the expectation of the growth of the grid connected sector. This sector was expected to experience by far the largest growth compared to stand alone non grid connected applications of PV. Although here no direct advantage is given to c-Si technology, indirectly this would turn out to be the case. That is because the first big boom in diffusion of PV would later on be the German rooftops with c-Si modules, connected to the grid. This was because c-Si would turn out to be the most feasible technology for roof top installation at the time of the start of 100,000 program. Of course this is not necessarily a permanent thing, but at least it was the case at that time. These expectations on the growth of the grid connected PV market and its dominance created technological expectations (e.g. technological conditions that must be fulfilled for grid parity to be reached in the feature etc.) and favored the technology that was most suitable on the short to mid-term, namely c-Si technology. Compare this to, for example, the hypothetical scenario where non grid connected application in, lets' say, clothing and textile was considered to be the most promising market for the future in terms of growth. In this application, flexibility of the module is much more important than efficiency and thin film solar cells (which have in general lower efficiencies) suit this type of application better because one of their advantages is exactly the opportunity of flexibility (at least until the advent of c-Si thin film cells in later periods).

In the next period, it was expected that thin film PV technologies (i.e. a-Si) would soon make PV profitable. This in turn sparked interest in the form of entrepreneurial and R&D activities in the field of TF PV, as c-Si PV did not make PV profitable at this point in time. This seemed to have been misplaced optimism, as neither TF PV nor c-Si PV would be profitable on the short to middle term without significant and costly financial incentives. This optimism regarding TF PV was at the root of the competition between the different PV technologies. From a governmental perspective, a preference was given for R&D on established PV technologies or at least those which were perceived to be established in the near future. Naturally, this did not include organic PV technologies.

The apparent preference for thin film (especially a-Si, and then CIS) continued for a while in the "pre-boom" period, which was indicated amongst other things by the number of papers on this PV technology as well as analyzing the amount of papers on different PV technologies that received funding. Nonetheless, the government kept a broad range of technologies in portfolio and research on multiple PV technologies was funded by the government. Thus competition was present between the different PV technologies from this perspective in that thin film technologies were given more R&D importance in R&D institutions and from government. However, simultaneously other fundamentals were laid down for guidance of search into another direction. This was due to the 1000 roofs program (1991-1994), which was itself the result of apparent expectations regarding the grid connected sector on the German roofs. But the program also created further expectations, as it gave a signal to the PV sector of a potential start of market formation. Furthermore, there was the notion of sunk costs that were made during the program, which triggered further activities leading to other programs later on. This was mainly in favor of c-Si, which is why it is relevant to mention under the heading of competition here. The reason that c-Si was favored particularly, as has been mentioned more than once already in this thesis, is because of the fact that c-Si PV was the most suitable technology for power generation on the roofs at the time. Not only was it economically more attractive, but also in terms of experience gained in operating such a system as well as knowledge gained on long term functioning (i.e. it had been shown to work). Thus, c-Si PV in this way could surf along on the growing call for renewable energy that happened to, for a large part, take a starting form of grid connected application on the roofs.

This was later expanded in the 100,000 roofs program. While goals for renewable energy generation were present in Germany and also of a general nature, the support with regard to PV seemed also to be of a general nature, i.e. in the form of the 100,000 roofs program, not specifically for any PV technology. In practice however, the same issue discussed earlier occurs, in that c-Si PV was still the most suitable technology for such a program, due to its higher efficiencies (and thus lower area related costs) and the experience gained using the technology. Thus the 100,000 roofs program, besides creating a large market for c-Si technology, also made c-Si PV even more practically relevant. It is therefore not surprising to see that the number of papers on c-Si cells surpassed that of TF technologies for the first time in this period. Yet it is important to note, that the research into c-Si around this period was partly undergoing a transition from classical concepts towards c-Si thin film concepts, i.e. producing thinner wafers in order to reduce the costs. For traditional c-Si cells there was nonetheless still cost reduction potential expected (Goetzberger et al., 2003). However, as c-Si was becoming more practically relevant, the cost reduction potential for this technology also became more relevant and thus new ways were taken such as thin film c-Si cells which were researched which is evident in this period.

In recent times c-Si PV got priority in terms of R&D funding from the BMU, as was shown earlier in the context of the 5th federal energy research program. It thus seems that eventually when c-Si PV experienced such a boost compared to the TF technologies, this created a notion of "sunk costs", where it was considered to be more effective to use the gained experience and knowledge and build upon this in subsequent periods. Thus, even though c-Si PV was not theoretically the most suitable PV technology, it received the majority of R&D funding within the research program.

12.5 Function 5: Market formation

Early on the small PV market was more balanced in terms of market sizes of the different technologies, although c-Si and a-Si were practically only the relevant technologies. This was changing only around the end of the 90'ies, although the foundations for this movement were already laid much earlier. As c-Si had a head start as has been previously described, it was the most suitable technology for outdoor demonstration projects. When the 1000 roofs program started (1991-1994), which was not purely a market formation program, this was the case, and also when the boom in diffusion started this was the case. The 100,000 roofs program was bound to favor c-Si PV over the other PV technologies due to its economic advantages. Thus although the support for PV for market formation was general in a direct sense, it was specifically in an indirect sense for c-Si PV, as it greatly facilitated the growth of the c-Si PV market and industry. The effects of this have been seen in chapter 11 where the production of c-Si PV was much more than that of TF PV, and the market for c-Si PV quickly grew and the proportions shifted towards about 90% c-Si PV dominance in the market compared to 10% for TF PV.

However, the 100,000 roofs program (1999-2003) went together with the famous EEG feed in law. This EEG law is still running, in contrast to the 100,000 roofs program which was for a more limited time period. The EEG law also played a vital role in the diffusion of PV in Germany, and since it is still running it benefits both c-Si and TF PV. It can then be questioned if the EEG law favors a particular PV technology. Although the EEG does not directly distinguish between the PV technology in terms of its' feed-in tariff, it does distinguish between ground mounted projects and roof systems in that the tariff is lower for ground mounted systems (up to 10MW) than for rooftop systems, even for large roof top systems with comparable sizes as that of a large ground mounted system (Wicht, 2012). In order to have, let's say, a return on investment of 10% after 20 years, the system price/kW must be considerably lower for ground mounted systems (Wicht, 2012). This also holds for large rooftop installations, in that system prices/kW must be lower for such installations than for residential rooftop installations (up to 5kW) in order to get the same ROI after 20 years. Another factor to take into account is the fact that c-Si modules need less space to produce the same amount of kW (due to their higher efficiency) in comparison to TF modules. This gives rise to the expectation that c-Si PV will be more suitable for applications where the area is restricted, whereas TF modules could be more competitive in the future where there are no practical restrictions for the system in terms of area. This would imply that different markets can coexist for PV, e.g. residential systems and ground mounted systems, each with a different most suitable PV technology (O'Rourke, 2012). But, if we consider the fact that the cost/kWh of different PV technologies are now close to each other, i.e. within a range of 10% (O'Rourke, 2012), it becomes evident that for large ground mounted systems to get the same ROI at the same cost/kWh, this will take longer for TF than for c-Si PV. Since most of Germany's suitable roofs are still uncovered with PV, c-Si PV therefore seems the most viable economic option for now. However, this does not mean that the largest growth will take place in the residential roof top sector, as not everybody has access to these rooftops. If investments from house owners in roof top systems will be larger than investments from, for example, utilities in ground mounted systems, is not yet clear. And even if it was clear, it is not decisive yet which PV technology will be most suitable. In any case, the EEG law at the moment generates potential for both c-Si and TF PV technology. Which technology is most economical in what context requires a detailed economic analysis, even if we only consider static variables. If dynamics would be taken into account (e.g. developments in technology and feed in tariffs), even more complexity would be involved. Such analyses are beyond the scope of this thesis.

12.6 Function 6: Mobilization of resources

With regard to resources early on an aspect occurs which is related to points made earlier, namely that the semiconductor industry provided opportunities for the c-Si PV industry in terms of established semiconductor companies involved, which brought in resources for the initial research done on c-Si technology, but also expertise and human resources.

From a raw materials perspective, there never has been competition between the different PV technologies, and there probably never will be. This is obviously due to the different materials that are utilized in the different technologies or the abundance of the material (such as in the case of silicon for c-Si and a-Si).

The diffusion of PV technologies, either one, is dependent upon investments from involved parties. For example, the 100,000 rooftop program could never have succeeded without the investment of 10's of thousands of private house owners in PV systems. It can be questioned whether investors have a preference for certain kind of systems with a specific PV technology. First of all, it is likely that investors will not focus on the PV technology as a goal in itself, but rather on the PV technology that will give the most economic benefit. This is dependent upon a number of factors, for example the area related costs, the cost/kWh of the modules, etc. Second, the type of application determines for a great part the type of investor. For example, large ground mounted systems requires project financing and major construction. And this large scale utility environment is exactly the environment where thin film PV at the moment is at its best, due to a relatively favorable balance of factors (Laird, 2010). Since room for investments on such a scale became tight in recent years, some TF firms could not pursue further R&D in order to stay competitive with the c-Si PV sector, which caused them to go out of business (Laird, 2010). In any case, this shows there is competition between the different PV technologies due to the fact that they are close to each other in terms of cost/kWh, and it remains to be seen what dominant technology will emerge in what market segment.

From an industry perspective, the firms involved in the different technologies of course differ in size and available capital for R&D. Some firms do R&D in more than one PV technology, such as Q Cells, which is at the same time on of the leading firms in terms of R&D expenditure (Breyer et al., 2011). The core business of Q Cells seems to be in the field of c-Si PV, however the planned expansions in production capacity for c-Si and TF PV (CIS) was of a comparable size in 2008 (Q Cells, 2007). R&D expenses were not available from Q Cells.

On a federal level, in 2009 51% of funding for R&D was given by the BMU to c-Si wafer technology, compared to 14% for silicon thin film and 16% for CIS thin film technologies. Organic PV is funded from a different department, namely the BMBF.

On a European level in the Framework program, investments in c-Si wafer based technology were slightly higher than investments in TF technologies in the FP6 program, whereas in the FP7 program the investment in TF PV far outweighed the investment in c-Si wafer PV (Breyer et al., 2011).

12.7 Function 7: Advocacy coalitions

Early on, new advocacy coalitions were established from which originated several vital policy measures later on such as the feed in law and the 100,000 roofs program. Although this did not imply that advocacy coalitions were directly advocating c-Si PV over TF PV, indirectly this was the case as c-Si PV at this time and in the following years would be the most attractive option for private house owners and the like. However there was no advocating of specific PV technologies over others, seemingly because unity among the actors in the PV sector was at this stage very important in order to join forces and exert greater pressure on the government. Furthermore, especially early on the focus was more on PV as a generic concept and its contribution to the energy supply in Germany, rather than on what specific PV technology is best suited for this challenge. Since c-Si PV at this time was most developed and economical, c-Si PV was the obvious technology to be indirectly pushed by the various advocacy coalitions. However, over time more and more TF PV firms emerged, and were also represented in the large PV lobby associations, which represented more than one PV technology. It seems that not a particular kind of PV technology is advocated, but rather measures are advocated that benefit PV in general, and it is up to the different PV technologies to develop in a way so that they can lift with the growing demand resulting from the measures.

13. Conclusions and Recommendations

The research question to be answered in this thesis is:

What has been the state of functioning of and competition between the three generations of PV in Germany from a Functions of Innovation Systems perspective?

The sub-question that were answered in order to answer this question will now be answered.

1. What is the background of the current PV market situation in Germany?

Early on in the history of PV in Germany, the sector started out as a “by-product” from the semiconductor industry. C-Si wafer and a-Si thin film technology were both used and researched, although the balance was slightly in favor of c-Si in terms of market share. In this early period, high costs of PV technology was not the main obstacle, as the application of PV was in the area of space travel. However, it was apparently envisioned that c-Si PV would not be an optimal technology for larger scale application of PV, and a-Si thin film technology was increasingly seen as the alternative to replace c-Si eventually, and research into a-Si technology increased. At the same time however, c-Si was more established and used in demonstration projects and the like (learning by using), thus further entrenching the c-Si wafer technology as there were references and experience with using it over longer time periods.

This trend continued in the second period. Although the research done was very broad in scope regarding PV technologies, there was a heavy focus on thin-film technologies due to high expectations. Thus, the learning by searching and guidance of search were functioning. At the same time however, the 1000 roofs program, which was meant to demonstrate and gain experience with PV, was conducted using c-Si PV modules, thus further increasing practical knowledge (learning by using) regarding application of the c-Si wafer technology, as well as practical expectations related to its use. Thus seemingly non-constructive developments were taking place, from which it can be questioned on hindsight whether a different approach would be desirable in such a situation. This is a very difficult question to answer, especially due to uncertainty regarding technological developments. For example, it turned out that a-Si technology carried along serious obstacles (e.g. degradation effects), which were underestimated at first. On the other hand, it could be argued that such a development of PV technology was actually beneficial. This is due to the fact that the established nature of c-Si wafer technology, as well as practical experience with its use, increased interest for PV in general and showed its viability. Thus, even though thin film technologies were definitely getting behind with c-Si technology from the perspective of market formation, the c-Si technology can be seen as the factor protecting the early PV niche, proving PV to be a viable alternative for renewable energy, and thus sustaining interest and expectations regarding PV in general and other PV technologies. Thus c-Si technology can be viewed as functioning as a sub-optimal player in the team, being the only one on the team to score at least some points for the time being, scoring just enough to keep the PV team in the competition. In the meantime other TF PV technologies were not yet scoring, but their innovation systems were given the time develop themselves further and further (due to c-Si keeping the team in the competition), to get in the team later on and start scoring points. Thus knowledge diffusion networks were laid, and learning by searching was being done. Entrepreneurial activities in this regard were not so stable for PV technologies, but a basic level was present and necessary in order to meet the limited demand created by early demonstration programs and the like. Furthermore, connections were established between firms and R&D institutes/universities. Advocacy coalitions at this time seemed to have a generic view of PV technology, not specifically and explicitly advocating programs for one PV technology, although in practice the 100,000 roof program which would follow in the fourth period was suited only for c-Si wafer technology at the time.

2. *What factors led to the accelerated diffusion of PV technology in Germany?*

The main reasons that were identified were the start of the 100,000 roofs program and the implementation of the EEG feed-in law.

3. *How did these factors influence the development and diffusion of the different PV technologies?*

As the desire for a renewable energy household grew further and further, it seemed that the nearing boom in diffusion of PV was ready on the one hand to take along any suitable PV technology in its growth, not being intentionally aimed towards a particular PV technology. On the other hand however, the specific market where this boom would start, i.e. on the German roofs, was very selectively favoring the c-Si technology due to a number of factors outlined earlier in the thesis (mostly economic). Thus, when the actual boom started around 1999 due to the start of the 100,000 roofs program and later also the EEG, c-Si technology rapidly became more relevant from an R&D perspective, because of the issue of reducing costs further and reducing materials (for the silicon shortage that was expected due to the increased sales of c-Si solar cells, as well as to reduce costs). C-Si PV technology also attracted much new entrepreneurial activity, as the growing market offered opportunities for large volumes of PV module sales for German roofs. Also R&D into c-Si went up as indicated by the development of the number of papers. The relative share of R&D into thin film PV dropped. This raises the question why R&D institutes did not earlier on increase their R&D into c-Si technologies at the cost of R&D into TF PV, and why this only happened at the time the boom started for c-Si PV. On the one hand there is an obvious answer (i.e. c-Si was now much more practically relevant), but on the other hand it shows a lack of integration between the different parties in the PV sector. Had these R&D institutes known earlier on the future market growth of c-Si PV due to the 100,000 roofs program, and the need for cost reductions therein as well as material reductions (due to the coming silicon shortage), it is expected that they would have focused on this earlier on. Thus a more integrated approach with advocacy coalitions and government could have benefitted the cost reductions of c-Si PV more timely, however this would inevitably be at the cost of TF PV technologies.

In the latest period, the rapid diffusion continued even though the 100,000 roofs program had stopped. The main driver behind this from a market formation perspective was the EEG law which was still in place. However, as the demand was rising, increasingly the mobilization of material resources regarding c-Si PV was getting problematic, due to the shortage of silicon. It is therefore not surprising that the research into organic PV experienced a boom, and surpassed other PV technologies in number of papers published. C-Si PV remains to be dominant from the perspective of entrepreneurial activities as well as R&D. Nonetheless a very broad base of PV technologies appears in firm activities as well as in R&D. There is still vast potential on the roofs that can be used, but in the future increasingly space will be a problem, necessitating higher efficiencies for PV technologies in order to keep down the area related costs. Thus it can be said that in general, the different functions of the IS are functioning for PV, however, more specifically for c-Si this has been more comprehensive as functions such as market formation and advocacy coalitions (implicitly) worked in favor of c-Si PV, whereas this support was neither implicit nor explicitly for thin film and organic PV. Nonetheless, the playing ground has been more leveled in recent times due to the closing gap in terms of costs between TF and c-Si PV as a result of learning by searching, which gives TF more chance to benefit from learning by doing, using and market formation programs. Organic PV will steed need further development, while in the meantime the other PV technologies can keep up expectations and further create a market.

4. How did the different PV technologies compete?

Historically, it is evident that early on c-Si PV had a competitive advantage from the perspective of entrepreneurial activities originating from attention from the semiconductor industry. However, already early on there was also attention for thin film (a-Si) PV, although the a-Si technology lagged behind in terms of efficiency, making it inferior from a technological point of view. Early on it was still not known which market would grow most, and much expectations surrounding the a-Si PV technology therefore attracted entrepreneurial attention to a-Si next to c-Si PV. Thus competition early on was important in this regard. However when weight shifted from technological expectations towards the expectations of a growing market (i.e. with the advent of the roof programs), entrepreneurial activities were induced and influenced more by what particular market segment was experiencing growth at that time, and the corresponding most suitable PV technology (e.g. c-Si PV for roof systems). For example, if flexible PV on textile would be booming, it can be expected that TF technologies (which allow for flexibility) will attract entrepreneurial attention. However, as the market grew in favor of c-Si PV (i.e. in roof installations), the c-Si PV sector attracted most entrepreneurial activity. Thus later on the essence of competition regarding firms was originating from market formation rather than from entrepreneurial activities themselves. However, entrepreneurial activities kept a broad focus all along with regard to the different PV technologies, and as their costs come closer to each other, there will be increasing entrepreneurial competition as to what PV technology to focus on. This is especially the case with PV firms that develop more than one technology. Thus another shift can be expected where the market is less selective towards one specific PV technology (as the different technologies get closer in terms of costs), and more initiative is expected at the entrepreneurial side, for example in product differentiation (esthetic qualities, formulation of advantages of the specific technology, etc.) and cost reductions. Already a shift can be noticed in ground mounted systems, where more and more TF PV is used.

From the perspective of learning by searching, it is obvious that funds for R&D had to be divided between the different PV technologies. Initially a hierarchy seemed to be present regarding amount of papers on the different PV technologies, which could be seen in the competition analysis earlier. Thin films were clearly favored here over c-Si PV early on. However, the rise in papers regarding one PV technology did not lead to a decline in papers for another PV technology, rather there were synchronous ups and downs, indicating again that funding regarding PV was viewed from a generic perspective: In effect, if PV becomes more relevant in the eyes of institutes/government, an increase in papers for all PV technologies was witnessed. This showed that there was an explicit strategy to retain a broad focus and portfolio, and that there was uncertainty as to what PV technology would be dominant, if this would be the case at all (e.g. instead of coexistence). The hierarchy in number of papers changed after the boom in diffusion, as the positioning of the different PV technologies in the competition changed. C-Si was now higher in the hierarchy than thin film technologies. This is also reflected in the majority share of funding from the BMU (which does not cover basic research) for c-Si PV over TF PV after the boom. Also a new field emerged which attracted a lot of R&D attention from R&D institutes, namely organic PV which topped the number of published papers in recent times. The reasons for such a shift in hierarchy could be that after the boom, expectations had to be reset due to the huge advantage that c-Si achieved in terms of market formation on the German roofs. Issues with regard to c-Si thus became suddenly much more relevant (e.g. need for cost reductions, material reductions in the face of the shortage, etc.). The idea grew that dependency upon one type of PV technology is risky (as was shown by the silicon shortage), and that there were new materials at much lower costs usable for PV applications (although with a lower efficiency), which led to an increase in R&D into organic PV . From the perspective of learning by doing and learning by using, it is clear that c-Si was and is ahead in this competition, as production of c-Si PV has been much more than other PV technologies, as well as its use in terms of installed capacity. Early on there seems to have been a misalignment in Germany policy for that reason, since research was more focused on TF PV, but at the same time no measures were undertaken to stimulate learning by doing and using in order to induce market growth for TF PV. Such market growth could have further induced R&D into TF PV (as it would become more practically relevant) and lead to further learning by doing and learning by using, which in turn would make TF PV cheaper and more attractive for further use.

Guidance of search in the early period led R&D into thin film technologies, as they were expected to replace c-Si PV one day. Expectations were key in this regard, as they induced research into the different PV technologies and led to a broad focus, i.e. not only on c-Si PV. In fact, it is only expectations that lead the booming R&D into organic PV, as there are no immediate markets yet. Direct competition surfaced when government support had to be divided among R&D into different technologies, as has been mentioned earlier. A broad focus regarding PV technologies however was retained in terms of R&D throughout the different periods of time, although c-Si PV seems to be most favored from a government perspective in terms of funding. Targets were set regarding renewable energy contributions, however these were general in nature not specific to PV or a PV technology. The same holds for the installations targets in the 100,000 program in the sense that no particular PV technology was excluded from the program. However, in practice support for such targets was mostly given to c-Si PV, as it was simply the PV technology most used in the installations. Thus c-Si PV had a natural leading position, and the government did not do anything to change this in the market, except for R&D into TF which it supported, expecting that it would become competitive with c-Si PV just through this R&D. On hindsight it can be questioned whether this is “fair”, since c-Si PV *did* receive much support not only in R&D but also in terms of market formation/guidance of search regarding market/installation. At least this strategy has helped to gain experience with PV, build up a PV sector and sustain interest in PV. As time passes, differences between the PV technologies are expected to narrow down further in terms of costs/efficiency, and more and more experience is gained with TF technologies, thus making any relative expected continuation of diffusion difficult to predict for a specific PV technology. It is at least expected that c-Si PV will decrease in market share, as TF technologies become more and more competitive and will take up market share, although c-Si PV is still expected to remain dominant for the foreseeable future.

This relates directly to market formation. The TF technologies were no match for the c-Si PV technology in the roof programs, as c-Si PV systems were the overwhelming majority in the total installed PV systems, which is linked to the nature of these roof programs, as a roof installation has limited size, needing higher efficiencies. Furthermore, lower efficiency meant a larger system (to get the same amount of energy), thus leading to higher area related costs. Only on a larger scale TF became competitive, however this was not supported in the 100,000 roof program. In the EEG law however the support is more general, and is also for ground mounted systems. Therefore the current state of affairs suggests that coexistence is possible, with ground mounted systems using TF and residential systems using c-Si PV. However this is still too superficial to state at the moment, as it requires a detailed economic analysis to see what PV technology is most appropriate in what application, especially since the PV technologies are not so far apart anymore in terms of costs. It can at least be said that market formation favored c-Si PV far more than it did for TF historically, but this is not necessarily a bad thing for TF PV. This is due to the fact mentioned earlier that c-Si PV was already established and showed good results in application, thereby sustaining interest in PV and developing the sector further, giving TF PV the time to develop further while c-Si PV was running the show in practice. However, since the EEG (which started in the same period as the 100,000 roofs program) is still running and will be expected to keep running in the foreseeable future, thin film technologies were able to benefit from this as they developed further and became more competitive. Thus a more level playing ground exists today than in the past, where increasingly PV technologies will be close to each other in terms of the traditional parameters (e.g. cost/kWp), and thus will need to distinguish themselves on other grounds.

5. What lessons can be learned for the Netherlands?

The development of PV technologies in the Netherlands has not been under study in this thesis. Instead, the focus was entirely on Germany. However, now that insight has been gained into the development of the different PV technologies in Germany, an advice will be presented based upon some indicators of the PV market in the Netherlands as well as relevant background information. The focus of this recommendation will be from the angle of the comparative/competitive analysis of the different PV technologies in this thesis.

When looking at the Dutch PV market, it is evident that historically much less developments took place; there is much less installed PV capacity in the Netherlands as well as active companies, and a much smaller range of activities (Vasseur & Kemp, 2011). Furthermore, it has been shown that market support for PV technologies has not been reliable and continuous in the Netherlands, leading to uncertainty for investors. In Germany the support was given on a continuous basis and efforts made to ensure this were successful (Vasseur & Kemp, 2011). Thus, considering the analysis for Germany and the just mentioned facts, it appears that the Netherlands could benefit from the following recommendations:

1. *Strategically align market incentive policies with the strong aspects of Dutch R&D in PV.*
   In Germany, this was initially not done, which led to a knowledge base being developed for thin film technologies while only c-Si technology was gaining practical relevance and operational experience, leading to overwhelming dominance of the technology later on and a shift in research towards c-Si (as it became practically more relevant after the initial 1000 roofs program and the 100,000 roofs program). In practice for the Netherlands this effectively means that it must capitalize on its current strengths by aligning its market incentive policy with promising R&D into PV technologies and corresponding applications

that are most desirable from an economic and sustainable point of view. For the Netherlands, its strong points regarding R&D seem to lie in the fields of c-Si, a-Si and organic PV technology (Jabri, 2012). An examples by which this could be done is by stimulating the incorporation of a-Si by architects into the design of new buildings, as a-Si is more suitable for building integrated applications than c-Si, in part due to its flexibility. Another example is *already* (financially) stimulating the use of organic PV in consumer applications. One might argue that organic PV is not ready for this yet in the Netherlands, however the mere presence of the incentive will speed up the process of market introduction and will attract entrepreneurial activities for organic PV, and will ensure a market. Of course, these examples are conceptual and do not specify the financial measure as it is beyond the scope of this thesis.

2. *Initiate demonstration projects early on for promising technologies, even if they are not yet ready for market introduction.*
   Also in Germany this did not happen initially, as in demonstration projects or programs c-Si technology was used mostly as it was still the most economically viable option. This is understandable, however it contributed to the lack of learning by using for thin film technology early on in Germany. This hampered growth of expectations and put thin film PV on the background whenever previous references and operational experience was important in determining the type of PV to be used. Nonetheless, the knowledge base regarding TF technologies was growing. Therefore, in the Netherlands demonstration projects should carefully choose the PV technology not only from an economic or convenient point of view, but also with the eye on the desirable PV technologies of the future. An interesting practical example here is found in Nuon Helianthos, which had to stop its (novel) high potential production activities of a-Si PV recently (in September 2011). One of the reasons for this was the lack of investors in the technology, which was in turn partly caused by a lack of reference projects using the a-Si technology developed through the new process (Nuon Helianthos, 2011). Initiation of demonstration projects by the Dutch governments which employ high potential or strong aspects of PV technology in the Netherlands helps to establish practical knowledge regarding the application of the technology, which in the future will make it more attractive for investors to choose this technology for investment, as there will be less uncertainty regarding the technology. This in turn will facilitate a choice between PV technologies based on other criteria than convenience and uncertainty, such as sustainability, novelty and so on.
3. *Strike a balance between funding of R&D into desirable PV technologies on the one hand and sustaining interest and funding of entrenched technologies on the other*
   In Germany it could be seen that there was a clear hierarchy before the boom period in the number of papers about the different PV technologies. After the boom period, this hierarchy became chaotic, changed and resulted in a new although less clear hierarchy. This points to inefficiency in the R&D setup in Germany; it is as if after the boom it was a surprise that c-Si technology became the most practically relevant PV technology (due to the fact that it was by far most used), and the hierarchy changed as a result of it. On the other hand, c-Si technology helped to sustain the interest in PV as it was a working and viable PV technology which was widely implemented. The Netherlands can learn from this through keeping a distribution/hierarchy of research and research funding regarding the different PV technologies that is aligned with its market incentive programs on the one hand, and on the

other hand the Netherlands should not neglect technologies which are *at present (but perhaps not in the future)* most attractive, as such technologies can serve to show the potential of PV technology for the time being, while other more desirable PV technologies can spread in the market at a later point when they are more developed.

4. *Non-continuity in policy should not lead to inconsistency in policy regarding the different PV technologies.*
   Dutch policy regarding PV is notorious for lacking continuity, even though one program followed the other sooner or later (Vasseur & Kemp, 2011). If this lack of continuity is an inevitable possible outcome of the Dutch political system, and cannot be easily avoided due to institutional reasons, at least the policy should be consistent regarding PV technologies. It should take into account the effects of policy programs on the different PV technologies, even if a support program is stopped and replaced later on by a new one. For example, it is possible that a certain policy program is of such a nature that it supports mainly one specific PV technology B (e.g. due to this technology being most suitable for the funded type of applications). It might well be that this policy program is stopped abruptly later on and that new renewable energy policy is put in place (as has happened before). If this happens, it should be avoided that this new policy is now supportive of PV technology C at the cost of PV technology B, because this will partly undo the building up of the innovation system for PV technology B. The reason for this is that if PV technology C is now more supported by the new policy (due to some reason) than PV technology B, this will likely lead to less demand for PV technology B, forcing firms to close down and investments to be lost. Furthermore, it is not unlikely that R&D focus will be shifted again towards the now more practically relevant PV technology (as happened in Germany), partly causing expertise of researchers on PV technology B to become obsolete.

14. Discussion

14.1 Methodological issues

Competition

Applying the FIS framework for individual PV technologies was done in this thesis, as well as a study of competition between the same functions in different (PV) technology specific innovation systems. This approach to the study of competition led to interesting insights, but at the same time gave rise to the following issue: Regarding some functions competition took place between the different PV technologies only in a superficial sense, whereas a deeper look shows that the source of competition lies in another function. For example, it is very well possible that competition (for the understanding of competition in this thesis, refer to the theory section) exists between different PV technologies regarding the function 'Entrepreneurial activities', in the sense that (upcoming) firms must choose a limited amount of PV technologies amongst different PV technologies to start their activities in. However, when the market for PV technology B is growing much more rapidly than the market for PV technology C, it is not surprising that entrepreneurial activities will grow much more for PV technology B than for C. The source of this entrepreneurial preference for PV technology B is largely in the function 'Market formation' now, even though the resulting effects can be seen in the function 'Entrepreneurial activities'. Whether or not this can be called competition thus becomes a topic of discussion.

Furthermore, the understanding given to competition in this thesis is that the functioning of a certain function A for PV technology B should block or hinder the functioning of that same function A for PV technology C. This however does not take into account the situation where the functioning of a function A for PV technology B does not hinder or block, but neither enhances the functioning of function A for PV technology C, in effect having no significant influence. In this case function A for PV technology B would be functioning better than function A for PV technology C, but not at the cost of PV technology C, so it cannot be called competition. Nonetheless, this is a relevant effect which should be taken into account for policy makers, as it can lead to misalignment in policy also (e.g. if policy makers are assuming that certain policy helps all PV technologies while in fact it doesn't). I propose as a solution to this to loosen up the meaning term competition in this context, and perhaps choose a different name than competition, such as "respective development", "respective diffusion" or the like. Nonetheless, I think that competition in the sense used in this thesis is still the most relevant case of respective development, due to the fact that competition here means that not only is a function of another PV technology not influenced, but actually blocked or hindered.

Less recent information

In order to operationalize the ability of the innovation system to develop and diffuse the PV technology, it was necessary to have indicators per function of the innovation system in order to evaluate that function. Indicators in this regard were based on the work of Kamp & Negro (2009), Kamp & Prent (2009), as these studies are of a similar type to the present thesis. When conducting this case study however, some difficulties were found in using these indicators.

Technology specific information

One of the main difficulties in finding relevant information was that often there was no distinction made between the different PV technologies. This is not surprising, as such a distinction is not always relevant or the relevance is not always realized by the party providing the information. This led to much extra time needed to either find or deduce PV technology specific information in order to conduct the analysis. There is no easy way around this. It would be useful if in the future a distinction is made between PV technologies in the future whenever possible, as this will facilitate tailor made policy for PV technologies instead of generic policy.

Data collection

In this thesis a vast amount of data was available for analysis, but also a lot of data was not available. This leads to inaccuracies, although this is not expected to damage the general image of what was going on. For example, historical analysis of the functions in the innovation system was a large part of this thesis, however historical figures (e.g. R&D budgets)were often difficult to find. Especially when specific information was needed regarding the different PV technologies this proved to be a difficult task, as information more often than not was for PV in general. This means that alternative data had to be found in order to get an indication of, for example, R&D activities for different PV technologies, which was done in this case through analyzing the number of papers on the different PV technologies over the years. The drawback of this approach is that it measures only published R&D. Nonetheless it gives an indication of the *relative* R&D activities regarding the different PV technologies, which was one of the main considerations. Another difficult point was the increasing overlap between c-Si and a-Si technology in R&D through the development of tandem cells, which made analysis of the number of papers more difficult, as sometimes papers of an “unwanted” PV technology were included in a search for another PV technology. However this did not lead to major inaccuracies, as this effect could be limited by sharpening the search criteria.

PV technologies and phasing

In this thesis different phases were used in order to categorize developments and place them in the context of their time. A potential difficulty arises when one realizes that there are different PV technologies under study in this thesis, and that each of them have their own path of development. In generic studies that do not differentiate between PV technologies this is no issue, because conclusions are formed on the basis of general figures regarding PV. For example, if the total installed capacity (i.e. including all PV technologies) experiences rapid diffusion from a certain point in time, in a generic sense the PV technology experienced a “boom” in diffusion even though this boom might only happen for some PV technologies, and not for others. This was partly resolved in this thesis by choosing the phasing on the basis of policy programs or historic events not specific to any PV technology, but in practice especially these policy programs implicitly favored some PV technologies over others as has been shown and discussed earlier in this thesis. This makes the phasing relevant for some PV technologies and less for others. This can be resolved by distinct phasing for each PV technology, which will give a more clear image per PV technology, but requires more detail.

14.2 Theoretical issues

International aspects

While the FIS framework is a useful tool, it needs to be slightly adapted for different case study subjects. In the case of PV in Germany, international aspects not relating to Germany specifically played an important role. With regard to entrepreneurial activities, increasingly foreign firms were exporting their PV modules to Germany, thus making German entrepreneurial activities in PV manufacturing less relevant (although installers and the like remain essential). Also with regard to learning by searching and knowledge diffusion, PV showed to be of global interest, with international conferences being held where knowledge from all over the world regarding PV was being shared. Also expectations regarding diffusion (e.g. from US estimates on potential of PV in the grid connected sector as has been described) and targets (e.g. from the EU regarding share of renewables) were induced from international levels. In simple terms, I will call this globalization of the PV sector, which makes national boundaries increasingly less relevant regarding some functions. For example, Germany could in theory stop all funding for R&D, and focus on market formation. The German government would then rely on foreign R&D and would have to import PV modules from foreign countries after a while (as German modules would lack behind in development due to lower R&D activities), and still be able to stimulate the use of PV modules and its diffusion in Germany. This would casts doubts as to what functions are and what functions are not essential regarding the PV sector, if a case study for a particular country is undertaken.

My proposition in this regard would not be to necessarily add an eighth “international function”, as this would suggest international factors are essential, while this is not necessarily true if on a national scale all the seven functions are fulfilled. Instead I propose to treat relevant international factors as if they are within the innovation system under study. Not by pretending, for example, Chinese manufacturers to be German, but instead by merely looking at the influence these international factors have, and treat these influences as new objects within the innovation system. For example, if the diffusion of technology A is studied within a certain country B that has very little R&D/manufacturing experience with regard to this technology A, international entrepreneurial activities would obviously become a vital contribution to the diffusion of technology A in country B. The relevant international entrepreneurial activities can then be considered as replacing the national entrepreneurial activities function (under the assumption that import is possible).

This is conceptually shown in figure 14.1.

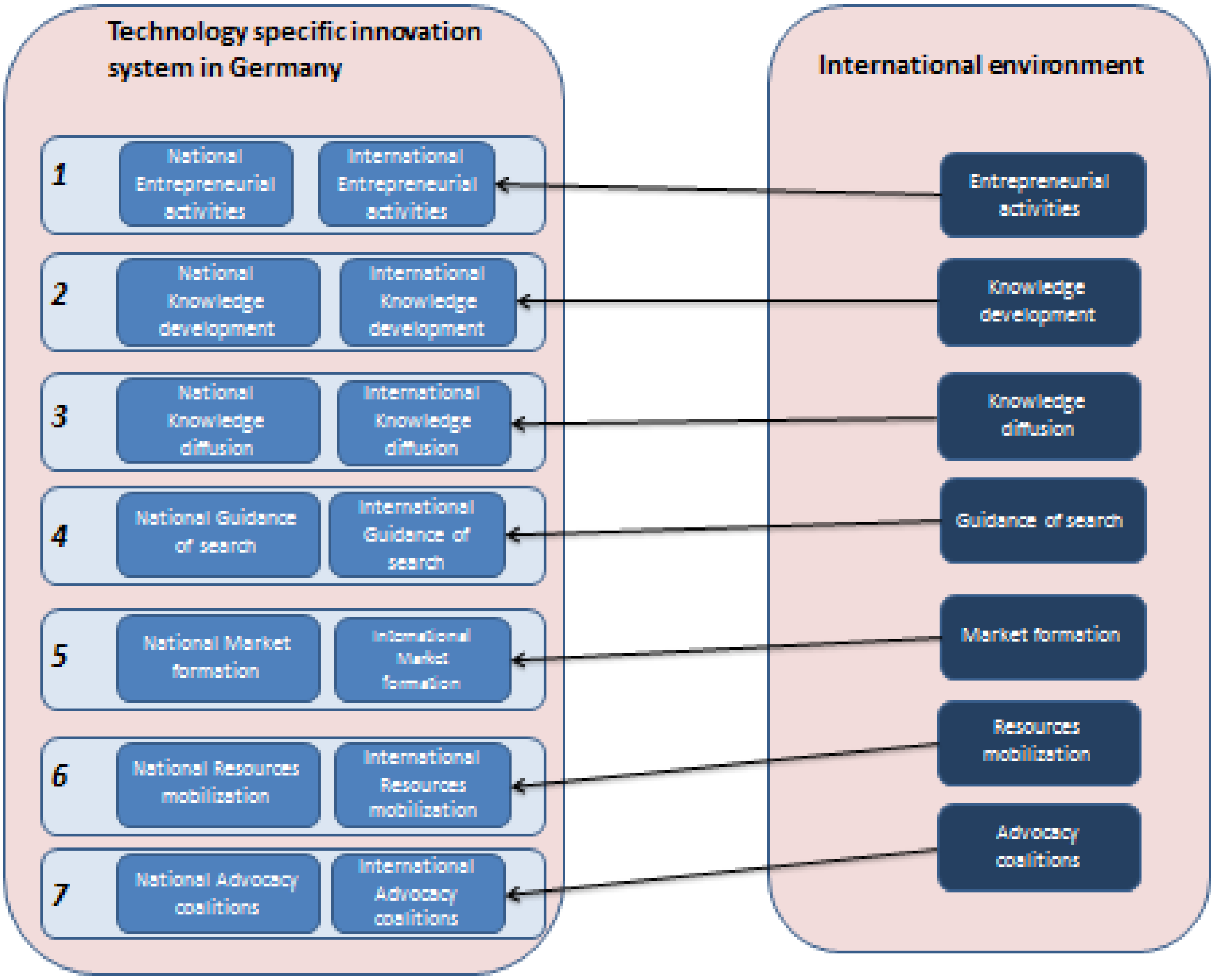


Figure 14.1: Conceptual representation of how effects resulting from international activities can be incorporated in the Technology Specific Innovation System for a specific country. The function in the national context and the effect of the international function are considered as under one function.

Dynamics of relevance of functions

It seems in a more general sense that the relative importance of the different functions is dynamic. For example, early on entrepreneurial are vital in a country if the technology is only just emerging, in order to demonstrate the technology in that country. Later on however, as globally the technology gets more established, the importance of manufacturers becomes less, and weight shifts more towards, for example market formation and advocacy coalitions. This is due to the fact that these are often nationally oriented (e.g. a policy program is initiated by a particular national government), and very relevant to create locally favorable conditions for the PV technology to diffuse. In my view the need for PV manufacturers at this point in time can be questioned, as there are many possibilities for importing PV technology into Germany, which of course relates to the point made regarding international aspects.

However, also regarding national aspects the relevance of the functions seem to change over time. For example, within the knowledge development function, it is conceivable that at an early point knowledge by using is very relevant in order for investors to get acquainted with the technology, and in order for references to be established, and so on. In fact, as has passed before, this lacked in Germany early on for thin film technologies in comparison to c-Si technology. Later on however, when the technology is well known and established, e.g. a technology like c-Si PV, learning by using becomes much less relevant and more focus is placed on learning by searching and learning by doing. Another example is lobby activities. In order to get a policy program or market incentive in place, advocacy coalitions played a vital role here. However, once such a program has been initiated up to the point that it leads to rapid diffusion, the importance of advocacy coalitions decreases, especially if the program is running continuously without end in the short term, creating no need for advocacy coalitions to work for a follow up program or the like.

Best strategy

Furthermore, for PV it was difficult to assess what functions were most important at what time, and this is perhaps also a subjective matter of perspective. For example, if we take the current situation in Germany, we could say that more market incentives would further stimulate diffusion, which is probably true. However, we could also say that more R&D would lead to further price reductions, further stimulating diffusion. Thus, what is the best way to go? Probably it will be a combination, however it would be interesting to be able to say something about the balance between these two from the perspective of the FIS framework. This would greatly enhance the applicability of the FIS framework for policy makers. Perhaps the use of simulation and modeling could be useful here; after all, the framework used in this thesis comes from a systems perspective, the interactions of which can be simulated. Of course the reality in this case is extremely complicated, but basic simulation processes of the functions and the different interactions could lead to new insights. Especially since it gets more complicated if we take more functions into account.

Function 6: Space as a resource

With regard to this function, an indicator seems to be missing which is getting more and more relevant in the future, namely the resource of space. As space becomes more scarce (which was an issue as has been highlighted earlier in this thesis), the price of space becomes higher, and thus different PV technologies will be competing for space more and more. Thus, I expect that this indicator will have to be added in more distant future studies dealing with PV.

Function 2: Production cost changes

A difficulty that was encountered regarding production cost changes and using this as an indicator for learning by doing was that changes in production costs cannot be attributed solely to learning by doing in the case of PV. That is because the field of PV was and is a developing technological field where R&D is done into issues such as using less material, which contribute to lower production costs. Such reductions in production costs cannot be attributed to learning by doing, but must be attributed to learning by searching, and thus this indicator for learning by doing has a weak point here. How big this effect is, is unknown to me but should be investigated for future research in order to ensure reliability of the indicator. I propose also that production cost changes is further operationalized to the level of understanding where these cost changes come from exactly.

Evaluating the functions

Whether or not the functions were working properly on the basis of indicators/activities is somewhat of a tricky issue, as the presence of indicators or activities do not necessarily imply that the function was properly fulfilled. Instead, these indicators or activities could have been present, but their quality could have been insufficient or something in that direction. I found this difficult to assess using the FIS approach. In effect it can amount to reasoning on hindsight: e.g., the diffusion started around this time, so apparently the market incentive program was good enough. Or, the prices were decreasing and diffusion took place, so apparently the function of knowledge development was fulfilled properly. In my view this amounts to the following problem: When is the functioning of a function good enough? The answer would be: When it minimally does what it is supposed to do. The next question then becomes: What is the minimum that it should do? This is a difficult question. For example, regarding knowledge development, we could say that learning by searching is needed in order to have knowledge to transform into innovation or to enhance the innovation, and so on. If R&D is being done, and the technology is developing and diffusing, this still does not tell us if learning by searching is properly taking place. For example, it could be that the pace of technology development is slow but compensated for by a strong market incentive program. This then makes it difficult to assess whether or not a function is properly fulfilled. It is then necessary to identify the key things such a function should do in the specific context of PV technology in Germany, in order to properly operationalize the function. This could be done, for example in the case of knowledge diffusion, by bringing together relevant persons of R&D organizations and firms in the PV sector, and have an expert meeting on what specific and concrete activities/processes are essential for proper fulfillment of the knowledge diffusion function. These activities/processes can then be the new indicators for the function knowledge diffusion, and future research on PV in Germany (perhaps other countries also, although this could be questionable due to the different situation) can then make use of these indicators. Also such experts meetings in this context could result in some quantitative data on the minimum level of fulfillment of a function, e.g. a minimum of three conferences per year is deemed necessary or the like.

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