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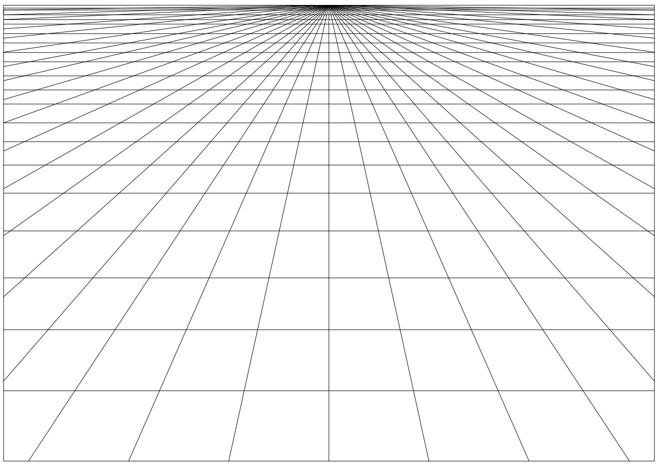

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The Establishment of the Solar Cell Industry in Norway –

Systemic Interaction and Path Dependency

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Abstract:

Solar cells have the potential of contributing to a larger share of total energy production being based on renewable energy sources. The technology has several advantages, but despite these the increasing contribution to total energy production, and increased diffusion of technology, depends on the ability to compete with other energy sources. In order to become increasingly successful and competitive solar cells have to be produced at lower cost. This paper analyses the economization efforts employed by the Norwegian solar cell industry. Moreover the paper is aimed at explaining the industry's establishment process of becoming embedded within the national system of innovation. Due to path dependency issues the mode of production has a characteristic national flavour, which has made the industry highly competitive within a global growing sector. The paper argues that the establishment has depended on technology and knowledge bases originating within the systemic contexts of both the sectoral and the national innovation system. The combination of path dependency and openness of the national innovation system to sectoral influence is seen as a decisive factor in explaining the establishment of the industry. I argue that the new combination of existing entities through learning processes results in technological and institutional change in the national system, which generates heterogeneity. By analysing the establishment of the Norwegian solar cell industry the paper argues that *i)* the Norwegian industry through its path dependency is becoming increasingly competitive *ii)* which leads to increased technological diffusion and *iii)* that the establishment contributes to growth within the national context.

Keywords: Solar Cells, Systemic Interaction, National Innovation Systems, Sectoral Innovation Systems, Path Dependency

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Chapter 1

1. Introduction:

Solar cells are a renewable energy technology with the potential to contribute to cleaner energy production. Even though the current contribution to total energy production is little, solar cells, or photovoltaic technology, are a growing renewable energy technology that has several advantages. Some of which are; no noise or emissions, off grid installation, no moving parts, no maintenance and a long life-time. Despite of these advantages the increasing contribution to total energy production, and increased technological diffusion depends on the ability to compete with other energy sources. In order to become increasingly successful the energy producing solar cell systems have to be produced at lower cost.

Besides the fact that solar energy has a large potential of contributing to environmental issues the industry experiences high growth. Thus the industry is becoming increasingly interesting also for economic reasons. The solar cell industry has grown forth with remarkable pace in Norway the last decades. Scanwafer, a central firm in this development, has for instance since the start-up in 1994 grown into a multinational billion dollar company now named Renewable Energy Corporation (REC). The company stands out as a successful actor both nationally and globally, and has become leading in this sector of great environmental, social and economic potential. Furthermore Norwegian companies like Elkem and Norwegian Silicon Refinery are also present in the industry. Despite of its geographical location, which is not highly suited for usage of solar cells on a permanent basis, Norway has become a central location for technological developments within the field. Furthermore Norwegian companies have become central much because of the ability to decrease costs of production. The reduction of costs has been particularly focused on the high cost upstream levels.

The paper analyses the establishment of the Norwegian photovoltaic (PV) industry by asking two interconnected questions. The first addresses how companies in Norway have become market leaders by asking *how* and *why* such an industry has been established in Norway. The industry is highly focused on the production of Silicon and wafers which are upstream products. The second research question is highly related to the first, and asks why the industry is focused on producing these upstream products? In extension of the latter; can the mode of production of the industry be tied to path dependency issues of the Norwegian national system of innovation? In analysing these research questions I argue that *i)* the Norwegian industry through its path dependency is becoming increasingly competitive on a global scale *ii)* which leads to increased technological diffusion and *iii)* that the establishment contributes to heterogeneity and growth within the national context.

To explain how the Norwegian industry has become a leading producer of photovoltaic technology I apply the systems of innovation approach. The innovation processes involve a set of organizations and interactions at the same time as the technology development processes are complex. The systemic approach to innovation provides the analytical tools, and is suitable because of its dynamic ability to structure the multiple factors mattering in innovation processes. In explaining the establishment of Norwegian firms within the solar energy sector a central issue is to analyse how new combinations of existing technologies and knowledge bases contribute to new modes of production. This paper will argue that such new combinations arise through the interaction between different systemic levels of aggregation. Therefore both the national and the sectoral aggregation of the systems of innovation approach are applied. The analysis of the interactions amongst the two systems gives us a broader scope than an understanding of the innovation processes solely based on a national focus. Photovoltaic (PV) technology has been present for decades, and a global growing sector exists. The paper addresses the developments within the Norwegian national context, but emphasizes the role of input from the sectoral system. In fact the sectoral system has played a key role in the establishment of the industry in Norway. The structure of the industry is determined by elements originating in the national as well as the sectoral system of innovation. I will show that in such a development the existing segments of one system (the national) are combined with existing segments of another (the sectoral), which generates heterogeneity within the national system. The combination of path dependency and openness of the national innovation to sectoral influence are seen as decisive factors in explaining the establishment of the industry. The paper is therefore a contribution to the recent debate on the interaction between different systemic levels of aggregation within the systems of innovation tradition, namely the national and the sectoral (Castellacci 2006, Moen 2006).

Furthermore, to explain the focus on upstream products of the Norwegian industry the national influence on the mode of production is analysed. The characteristics of the national system influence the features of the sectoral system of innovation. Here issues of path dependency become important to explain why the Norwegian industry is focused on the production of upstream products. Moreover I argue that due to path dependency issues, the mode of production has a certain national flavour, which has made the industry highly competitive within a global growing sector.

The concrete analysis will be carried out through a study of the technology itself, as well as the related innovation processes in the context of innovation systems. Photovoltaic technology is constructed on a set of technological levels. In this paper this results in the distinction between Silicon, wafers and modules. The raw-material input, Silicon plays a significant role throughout the whole technological value chain, as well as the cutting of Silicon wafers. Silicon and wafers are also the technological levels around which the Norwegian industry is focused. This paper will therefore analyse the role of these technological levels related to the production of photovoltaic technology.

A set of bottlenecks, both of a technological and societal character can be identified related to this emerging industry. These challenges are seen not only as barriers to be overcome, but also as dynamic drivers of growth. A bottleneck of particular centrality is Silicon, where a key factor is the demand for a high degree of purity. Up until now the global sector has been relying on scrap and rejects from the electronics industry, which has shared the purity requirements with the photovoltaic industry. The photovoltaic industry has experienced high growth the last years, making Silicon demand higher, at the same time as supply has been unstable. Silicon supply is therefore a central issue for the whole industry. I argue that over time the dynamics related to the challenges or bottlenecks cause growth and development of the sector. These dynamics are highly influential with respect to innovative activities, markets and R&D. Therefore the dynamics within the sector affect and motivate all components of the innovation system in their patterns of behaviour.

There is a large body of literature concerning the nature of photovoltaic technology. To a large extent much of this literature is either discussing technological determinants or societal issues concerning technological diffusion, and energy policy. Hence a study applying the systems of innovation approach is useful and important in the analysis of these industrial innovations, and also in explaining how such an industry is established within the Norwegian national system of innovation.

Following this brief introduction chapter 2 discusses the applied research strategy. Chapter 3 gives an overview of the technological fundament of discussion in this paper. The descriptions presented here are to a large extent general, and are meant as an introduction to historical and technological aspects of importance. These are also given to create a fundament for the following discussion as a means of understanding the innovation processes that are studied. In chapter 4 specific innovation processes are presented and analysed in light of the technological descriptions. The innovation processes are presented in light of the systems of innovation approach. Here a focus lies on technological foundations, learning, knowledge and the relation to technological trajectories and path dependency. The innovation processes of the industry are here divided into three interlinked phases. Chapter 5 discusses the innovation processes on the level of path dependency, material choice and the role of systemic lock-in. Some implications regarding policy are also made here. In chapter 6 I summarize the presented material as well as finishing remarks are made and conclusions drawn. This paper will use theory and empirical material simultaneously throughout most of the paper to describe the dynamics of the establishment of the photovoltaic industry in Norway. These dynamics are also the reason for not separating theory and empirics excessively.

Chapter 2

2 Research Strategy:

2.1 Case Study Research:

The STS tradition has been based on the usage of various methodological forms, largely due to the large number of academic traditions existing within the field. This is the case also in general within social sciences, where there are several ways of doing research. Different approaches have their own set of advantages and disadvantages. An important starting point is that the strategy used should correspond with the research questions. In this case I have asked *how* and *why* the PV-industry has been established in Norway, and furthermore *why* this industry is focused on upstream products. In addressing such how and why questions the preferred strategy is the case study (Yin 2003: 7). Furthermore a case study is a preferred strategy when …"a how and why question is being asked about a contemporary set of events over which the investigator has little or no control" (Yin 2003: 9). In this case such a strategy is fruitful, much because of the complexity of the object of study. Moreover the focus of the paper, the photovoltaic industry and its related innovation processes, are contemporary events or processes, over which I as an investigator or researcher exercise little control. This makes the case study approach not only fruitful, but also necessary.

Innovation is something that cannot be pinpointed as a single event, but is a cumulative *process* (Lundvall 1992: 8). Furthermore innovation is not a well-defined linear process, but rather a continuous, changing and heterogeneous one (Kline & Rosenberg 1986). Such characteristics are certainly reflected in the innovation processes and developments of technological change that are to be described in this paper. They are intricate, comprehensive and complex, at the same time as they are gradual and cumulative. The heterogeneity makes the case study a preferred approach. Furthermore, given the nature of the innovation process this study enters the development at a given point in time. The ever changing nature of innovation processes therefore allows only a glance at what actually has happened. When addressing how and why questions the case study approach is preferred because such questions are explanatory and deal with links that need to be traced over time (Yin 2003: 6). In seeking to explain these innovation processes I therefore also attempt to look back in time and seek out elements that can be said to be of importance today. A part of the paper will concern itself with issues of path dependency. At this point theory and methods interact. Such theoretical assumptions have not only been theoretically important in the writing of the paper. They have also been of methodological importance in the sense that such theoretical assumptions give rise to certain non-rigid cognitive schemes which affect the research process. This goes for both the search for information as well as the interpretation of the gathered information. An important point where a case study is distinguished from related approaches such as grounded theory is its relation to theory. As mentioned, some theoretical aspects can be seen as operating as cognitive schemes. Such an approach has not always been approved in the field of qualitative methods at least not in the grounded theory approach (Strauss & Corbin 1998). Flick (2006) states that the aspirations of early grounded theory of being a tabula rasa, a blank sheet, in the research process to a large extent are visions of utopia. There exists little that has not been researched, or at least there exists little that cannot be tied to any previous research in some way. In this study I have used existing literature and information as a basis for guidance throughout the research process. Furthermore an important part of the research process is to make theory development a part of the research design (Yin 2003: 28). In this case some theoretical ideas related to existing topics like path dependency and innovation systems have not only been guiding the research design, but has also been important for the generating theoretical assumptions along the way that can be seen as a contribution, or widening of existing theory.

In this sense the paper will use the systems of innovation approach as an open and guiding framework. The approach is seen as fruitful not only in structuring the paper, but also in retrospect as guiding in the research process. Innovation systems are often seen as open systems, and are therefore easily applicable to a variety of cases and topics. In this case the approach has been useful first as guidance when seeking out informants and other sources. For instance the systemic approach on a theoretical basis proposes that multiple sources operating in a systemic context matter for innovation. Therefore a wide variety of organizations and institutions potentially have contributed to the establishment of the industry. The systems approach has therefore first of all been guiding as to where I have searched for information, and what kind of informants I have used. Therefore I have searched for information not only in firms, although it is the firms that do innovation, but also in public agencies, policy documents and so on. Equally important; the approach also has been guiding regarding the nature of the information that is searched out. In this sense it may be stated that the systemic approach has been useful in organising and structuring interviews, at the same time as it has guided the nature of the questions posed to my informants. This is not to say that the approach has been overtly structuring for the research, rather it has functioned as a conceptual framework during the process.

2.2 A Case Study of the Norwegian Photovoltaic Industry:

In the process of seeking relevant data and information in a complex context an important start has been to find out what the objects of study find important, and why. There exists little literature or structured information directly concerning the empirical issues analysed in this paper. Nevertheless there exists much literature that concerns elements presented in the paper, such as technological characteristics and the theoretical and empirical approaches to innovation and innovation systems. This has in some senses guided the research, and which topics that have been discussed during interviews. The first step was therefore to map and gather data and information that were useful as such guiding. In the process I have chosen to use various sources of information. An important source at early stages has been articles and literature concerning and describing the technological nature of the artefacts and processes presented of this study. This literature is in this paper used both as empirical and theoretical material interchangeably. By this I mean that what is a theoretical fundament in for instance physics or chemistry in this paper is used as empirical material helping to understand and explain innovation processes and processes of technological change.

In case studies an important approach is to use multiple sources of information. The main methods are based on semi-structured qualitative interviews. In addition, and equally important to the interviews other sources like web-sites, annual reports, technological descriptions and presentations have been used to further broaden the perspectives. Yin (2003) states the importance of using multiple sources of information. In fact it is argued that to be able to show a broad picture several factors, like documents, archival records and interviews should used. By and large anything that can be informative in relation to how and why this industry has been established is viewed as potential sources, but of course critically revised. In this paper I have used such sources interchangeably.

The PV-industry sector is rather young. Even more so in the Norwegian national context, and can be said to have grown at a fast rate in Norway during the last decade. There are rather few, but relatively large actors in this sector, at the same time as there exists a number of different technologies along the value chain. The first, but not always easy task, is finding suitable interview-objects. In this case, having little knowledge of the industry beforehand, the initial orientation processes were quite time consuming. Not only must the organizations themselves be mapped, but also what they do, and in what way. An even more complicated task was finding suitable interview-objects. The interview-objects which this study is based upon are, were selected with a background in several factors. First of all they had to be partakers within the systems that I set out to study, either actively through industrial or research efforts, or passively contributing with knowledge on related issues. Second; diverse actors with backgrounds in different elements of the system had to be chosen, although the focus has been on producing organizations. Third, the informants had to have in depth knowledge of their specific field. For the purpose of studying innovation processes the choice has been made to include actors on different levels of success marketwise. This is to ensure some level of symmetry, and thereby upholding the possibility of discovering information that would not be found in a study solely based on successful actors. The informants used in the paper consist of firms and public agencies. They are presented briefly at this point with the intention of giving a short introduction of the organizations before embarking more detailed descriptions in the following.

The processes of finding informants and other sources for information have been time consuming. Nevertheless this has been an important part of the process of gathering relevant information. Moreover this process has been a learning process of the characteristics of the industry. The interpretations presented in this paper are formed on a personal basis throughout the period of writing. The arguments presented must therefore be seen as one side of the story.

2.2.1 Key Informants – Oral Sources:

- *Firms:*

- *Renewable Energy Corporation* (REC) is the largest firm in Norway producing photovoltaic technology. It is also the largest company globally producing all levels of the photovoltaic value-chain, from Silicon feedstock to finished modules. The choice of this firm has a background in the success it has had in innovating and developing processes. Moreover Scanwafer, which now is a part of REC was the first firm in the Norwegian context concretely related to PV-technology production. REC is highly interesting because the company has been successful in implementing all parts of the value-chain in the firm. REC has a large market share internationally, and aims to produce cost-effective solar energy technology. The empirical material will be based both on interviews and other sources.

- *Norwegian Silicon Refinery* (NSR) is a small research based firm concentrating on the production of high grade Silicon; so called Solar Grade Silicon (SoG). This company has yet to establish large scale production, but has made interesting developments in relation to new ways of producing Silicon for the PV-industry. Nevertheless the innovation process of NSR can be said to be “incomplete” in the sense that the company not yet has reached full scale production, and does not produce commercial goods. This aspect in itself is interesting because it can give some pinpoints as to what matters when innovating research results brought forth in the laboratory.

- *Elkem Solar* is a large industrial company, within the process industry, with a long history in the production of Silicon and other materials. Elkem Solar has in recent years focused on pursuing new production processes for high grade Silicon for usage in the PV-industry. Pilot plants for large scale production are in the making, and Elkem are through this seeking out a position within the PV-sector, specialising in Silicon. Elkem is an interesting case first of all because of the production of Silicon for solar cells, which is important for the production of PV-technology. In addition Elkem has a long history in the production of Silicon, and has been central regarding the establishment of the industry. Furthermore there are tight ties between Elkem and REC that are to be analysed in the following.

- <u>*Public agencies:*</u>

- *Norwegian Pollution Control Authority (Statens forurensingstilsyn)* is a governmental agency concentrated on environmental issues. The project “miljøteknologi”[1] is located at SFT. This project has aims of mapping what can be done to promote the usage and development of environmental technologies. The information from SFT is of interest

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[1] Environmental Technology

because their have first hand knowledge of development of environmental technologies, and related regulatory bodies.

- *The Norwegian Board of Technology (Teknologirådet)* is an independent advisory agency, which has done work on environmental technologies. This has in later years been transferred to SFT. Teknologirådet is of interest to this study because they have made early efforts in relation to environmental technologies.

2.3 The Limits of the Research Strategy:

Any research approach has as mentioned its advantages and disadvantages. One such disadvantage is related to generalizability, which is a complex and debated topic regarding case studies. I will not address this debate in any length, but rather state in line with Yin (2003) that case studies are generalizable to the extent that they can be broadening theoretically. A case study cannot be generalized to populations, but to theoretical propositions (Yin 2003: 10). One aim of this paper, which was also stated initially, is to contribute to the understanding of the establishment of the photovoltaic industry in Norway, and throughout such an analysis also contribute to debate on interactions of innovation systems. At this point it therefore can be stated that by analysing a specific case and specific processes this case study can contribute to expand and generalize theories related to the systems of innovation approach.

Furthermore the research has been carried out under the distinct framework of time and space of the ESST MA. Therefore when operating research project within a systemic context, where multiple factors matter for the processes that are studied, it is obvious that all factors of potential importance are not included. This means that there are limits also to the data material, and what this material can explain. For instance this paper cannot explain why innovation systems in general operate in a given way, but rather why innovation systems operate in a given way in this case. Furthermore this paper can tell something about how innovation systems interact in this specific case, but not tell how interaction between innovation systems happens in general.

Chapter 3

3 Technological Introduction:

When addressing why and how the PV-industry has been established in Norway, and moreover why this industry is focused on delivering upstream products, a natural and necessary starting point is to look closer at what photovoltaic technology is. It is by opening the black-box of technology that developments can be identified. Moreover the social aspects of knowledge and learning become visible when analysing actual technologies and their related innovation processes. Social actors and actions stand behind each step of development. Furthermore social processes of learning resulting in various forms of knowledge compose the different technology development and innovation processes, making technology inherently social. This paper intends to open such a black box by giving detailed technological descriptions. The purpose of this chapter is therefore to give a general technological overview, before embarking on more detailed and concrete descriptions of technology development processes and innovation processes. This chapter therefore intends to give a brief introduction to the technological foundations to be discussed and analysed in the following. Understanding the technology development processes is not done fully without knowledge of the technological foundation. The aim of this paper is to describe the dynamics of innovation and how technology, science and society interact in a specific case. To be able to understand these interactions and dynamics a detailed description of the technological aspects is a necessity.

3.1 Technological Heterogeneity:

Technologies utilizing solar energy can be said to be heterogeneous in that different technological solutions exist. An important distinction is between so-called solar-thermal applications for heating purposes, and photovoltaic technologies that produce electricity. Regarding this technological heterogeneity, the paper will focus on Silicon based *photovoltaic* technology producing electricity. These devices are also referred to as solar cells. The industry in focus is in following referred to as the photovoltaic (PV) industry.

There exists a selection of technologies utilizing the photovoltaic effect to produce electricity. It therefore must be mentioned that a central discussion within both industrial and scientific forums is one of technological change and dominating designs. A challenging technology to traditional crystalline[2] PV-technology, which has been the dominating and pervasive design, is so-called thin film technology (Andersson & Jacobsson 2000: 1037). By becoming increasingly competitive regarding the central issues of price and energy viability technological change to thin film technology is by some (Andersson & Jacobsson 2000) argued to become the dominating design. This technology will not be analysed in this paper, but I emphasize that such the challenges of technological change contributes to the dynamics under which the industry operates.

The technological heterogeneity goes for the technological artefacts, as well as the technology used to produce the several elements that comprise a finished photovoltaic module. The scope of this paper will to a large extent cover the different ways with which such technology is produced. At the same time the artefact (the photovoltaic module) and the technology used to

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[2] Either in its monocrystalline or multicrystalline form (Goetzberger et al. 2003: 4)

produce (e.g. Silicon refining) is seen as interdependent. As shall be seen, the heterogeneity within the sector also gives rise to dynamics within the sector.

3.2 *The Photovoltaic Effect and Photovoltaic Technology:*

The radiation stemming from the sun has always been of use to people for several purposes. Solar radiation has been used throughout history for heating of water and buildings and is still used in so-called solar-thermal applications. It also has fascinated and inspired people to seek out solutions using this energy for different purposes. Such an interesting solution, both in respect to markets and especially the environment is the use of sunlight to produce electricity. One important way of converting solar radiation to electricity is by the physical effect referred to as the *photovoltaic effect*. The effect has been known since 1839 and was discovered by Henry Becquerel (Goetzberger et al 2003: 1). He discovered that a current was created when light struck certain metals. Another 60 years went by before Einstein laid the theoretical foundations for the photo-electric effect. Hence both the utilization of energy stemming from the sun, and the knowledge of how to convert the sunlight into electricity has existed for a long time.

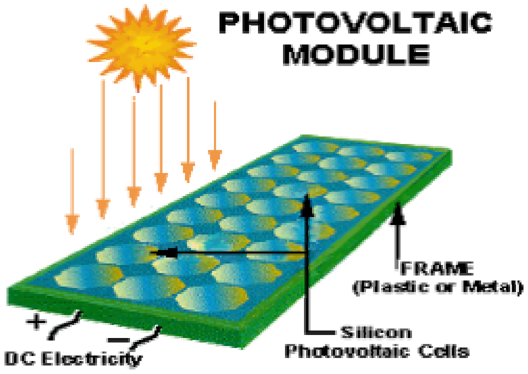

Figure 3.1: Photovoltaic module

Figure 3.1 is a simple depiction of a standard photovoltaic module. The essential technology is quite basic and consists of Silicon photovoltaic cells that are framed by plastic or metal. The photovoltaic effect is generally defined as "… the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto the system." (Goetzberger et al. 2003: 2). In short; when hit by sunlight layers of Silicon react and generate DC electricity.

The photovoltaic effect in itself is referred to as a research curiosity until researchers at Bell Telephone Laboratories turned this curiosity into a viable electricity producer about 50 years ago. The viability was increased by making higher absorption of energy possible and thereby increasing the output effect. Initially the technology was intended for usage as a practical power supply for remote telephone signal transmissions. Nevertheless the researchers created a technology that was first used to power early spacecrafts and satellites (Kazmerski 2006: 105). As with several other technologies, the US space programme was an important driving force in the early developments. Technology utilizing the photovoltaic effect has therefore become an attractive electricity production unit with the large advantage of making decentralized off-grid production possible. This potential has proven to be central because of the technological diffusion with a background in production of niche products. Nevertheless a great deal of complex innovation processes have been necessary for developing commercially available technologies utilizing solar energy the way we can see in the context of today.

3.3 The Innovation Time Span; Photovoltaic Technology in the Making:

The importance of distinguishing invention from innovation is clearly illustrated in the case of photovoltaic technology. Innovation is a term leading many of us to think of novelty, but should not be confused with invention. While "…invention is the first occurrence of an idea for a new product or process…innovation is the first attempt to carry it out in practise" (Fagerberg 2005: 4). Innovation is in nature often a time consuming process where the lag from invention to innovation often is considerable. In this case time lag can be said to be spanning from 1839 to present day. Such a time lag is often due to the lack of all conditions present for commercialization (Fagerberg 2005: 5). In the case of photovoltaic technology important conditions for commercialization have been attaining adequate efficiency levels at the same time as producing technology with such efficiency at a cost effective level. In short; the two key factors or conditions for commercialization from a technological point of view are energy viability, and cost. Thereby also cost efficient processes. I argue that the addressing of these issues is an ongoing process, and is the single most important objective of firms, including the ones in this study, in the context of today.[3] At the point of energy viability and cost the interplay between society and technology is clearly illustrated. The innovation journey of photovoltaic technology can be described as a development of increasing energy efficiencies and an increase in commercial potential, and thereby an increasing technological diffusion. Since the first solar cells were produced up until now the energy efficiencies have increased by large amounts. The first viable solar cells from Bell Labs had a conversion efficiency of 6% (Goetzberger et al 2003: 6). Commercially available

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[3] REC Interview

solar cells today typically operate at 15% conversion efficiency[4]. Thus there is a connection between the increased viability of solar cells and an increase of diffusion of the technology. Nevertheless, this must not be seen in isolation. I argue that what lies in between is highly important and that it is at this point that opening the black-box of technology becomes important. Not only of the technological artefacts themselves, but also equally important the technology used in production processes. What Kline &Rosenberg (1986) refer to as the "invisibility" of innovation certainly applies in this case. The many steps that must be taken to attain cost-effectiveness are filled will numerous and time consuming incremental innovations. A key factor is therefore the cost of production and product. Hence the *processes* used in production can to some extent be seen as determinants for usage of the technology. This is also a point where one can point out factors of both a technological and societal character to determine development. It is only in recent years that solar cells have begun to be an option for consumers, economically speaking, in certain areas of the world.[5] This is largely due to decreasing prices of the technology, increasing prices of grid power, at the same time as active policy work in this field has shown good results in some areas[6]. On a higher level of aggregation these user-producer interactions can be seen of great importance within the sector. On the technology, or the *producer* side, the developments have been made possible by an industry that has lowered production costs, while increasing the efficiency of the solar cell itself. On the *user* side the Governmental policy programmes in selected countries can be said to have contributed to the growth to some extent. At the same time the technological advancements have made the technology more effective and more reasonable (Søiland 2004:

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[4] This conversion rate varies in relation to technology. Results from laboratory test have been up to 30% efficiency. Nevertheless, commercially available typically are available at around 15%. Firms in the Norwegian part of the sector produce technology at this conversion rate. Source: http://www.solarbuzz.com/FastFactsIndustry.htm

[5] In peak power situations in California, electricity grid prices become of such a level that photovoltaic technology becomes competitive. (Elkem Solar Interview)

[6] Germany and Japan have for some years proposed and implemented governmental programmes advancing the usage of solar energy technology nationally. These policies either subsidise photovoltaic appliances, or base themselves on buying photovoltaic electricity at a price higher than grid price. (Ruud & Mosvold Larsen 2005: pp. 26-28). Such policies also make these countries among the largest markets for the Norwegian companies.

1). This paper will mainly analyse the technological developments driving the growth of the industry, but also acknowledge and point to the importance of social drivers, like policies, for diffusion and usage of the technology.

3.4 Diffusion and Economization:

There are important external factors present that affect the dynamics of the sector, especially those of total energy production. The topic of energy economics is a large issue. Nevertheless it is important to recognise that solar energy technologies exist within a context of dominating technologies that exceed the energy production of solar energy by large numbers. In fact solar energy production is but a small fraction compared to dominating forms of energy production, like water, coal and nuclear power. There is nevertheless a growing optimism related to the diffusion of PV-technology. This optimism is due to a combination of increasing energy viability and cost-reduction of production of processes. Furthermore; as diffusion increases prices decrease.

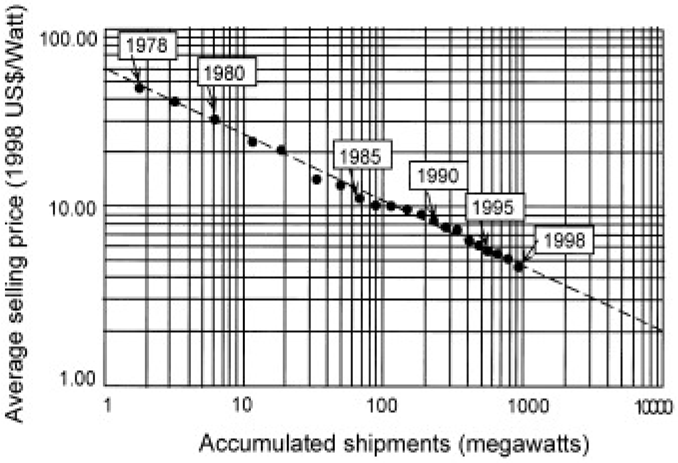

Table 3.1 Average selling price of photovoltaic modules versus total accumulated shipments

Table 3.1 depicts the average selling price compared to total accumulated shipments. It shows a decrease in prices at the same time as accumulated shipments increase. This means that the total amount of PV generated energy increases, at the same time as prices of finished modules decreases. In light of the focal point of the paper this depicts the general development of the industry towards an increased diffusion through the economization of processes and increased production volumes.

Therefore a related topic is the growth rates of the industry itself. The growth rates within the sector globally are estimated to be between 20-40% annually, depending on what sources used in analysis. Table 3.2 displays the global growth in the last decades, which shows production measured in total MW output. In the recent 5 years the growth of the European part of the industry has been as high as 40 % (Jäger-Waldau 2006: 1).

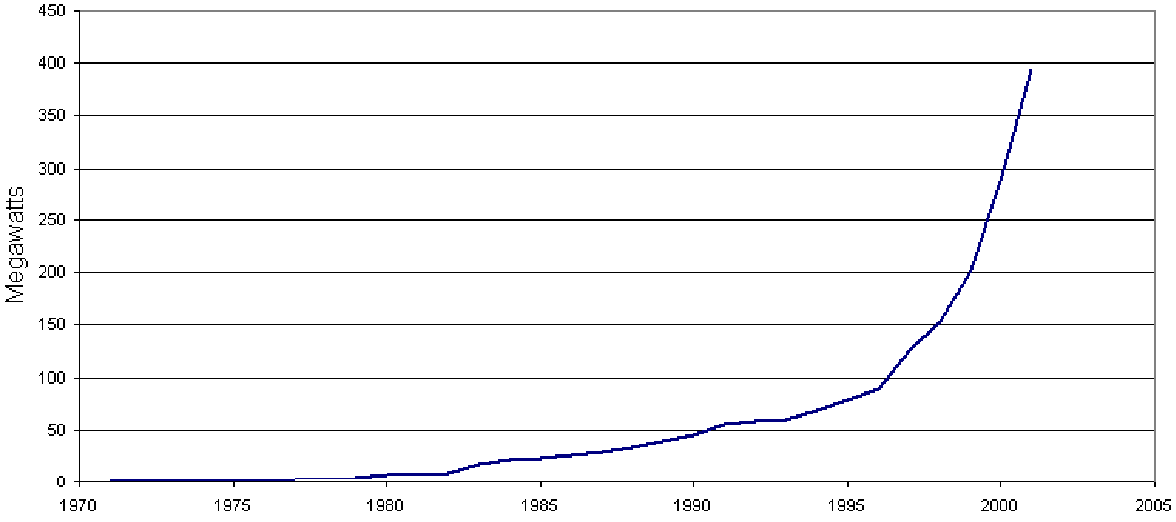

Table 3.2: World photovoltaic shipments in the period 1971-2001

Despite of the decrease in price and the high growth of the industry theorists (Jäger-Waldau 2006) are hesitant of viewing this as a development in direction of significant changes in the technological setup of global energy production. At the same time the efforts of the industry have been and still are the economization of processes in direction of increased cost-efficiency of processes. This is the key driver of the development towards a higher contribution of PV-generated energy. The following chapters will describe how the Norwegian PV-industry seeks to contribute to this development by working towards the reduction of production cost, on several levels of technology and production.

3.5 Technological Categorization:

There is a set of steps leading to a finished solar cell. In this paper the different technological steps will be described and analysed at three separate, yet interlinked levels. This classification of technologies has a background in the nature of the production process of solar cells. Three main areas of technology or levels of the value chain are identified; Silicon, wafers and modules. The two first levels can be labelled as upstream products. These two are also the levels were the Norwegian part of the sector is focused, and therefore also the focus of this paper. The technological descriptions in the following can be viewed as general. As shall be seen in the following process innovations related to production are of high importance in this sector. While describing the general technological foundation and history in this chapter, the following chapter will deal with the most important process innovations.

Figure 3.2 gives a compressed illustration of the photovoltaic production value chain, while Box 3.1 depicts the main technological levels and their main challenges. In this paper these challenges are also seen as dynamic factors or drivers of the sector. It is also new solutions to these challenges that often contribute to dynamics of the sector. To some extent the innovation processes can be seen as following the solutions to such challenges. The challenges to be overcome are many, and the knowledge needed to overcome these is of high importance and complexity. The Norwegian industry is highly focused on the two first levels. This paper will analyse the role of these challenges, particularly related to Silicon.

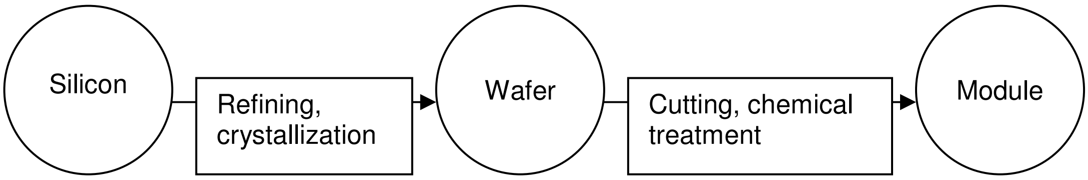

Figure 3.2: Photovoltaic production value chain

Technological component / Artefact	***Challenge / Dynamic factor***
Silicon	Cost, production method, melting, purity
Wafer	Thinness, sawing, chemical surface treatment
Module	Markets, users, cost

Box 3.1: Technological components and main challenges

3.5.1 Silicon:

The first and fundamental level of the photovoltaic technology value chain is *Silicon*. This material is the fundamental natural resource, raw-material, and building block in 90% of all solar cells (Mahrstein et al 2005: 1). Silicon based solar cells therefore has a large market share of commercially available PV-technology. Given that Silicon is the first level of production, it also is of a crucial nature to the whole value chain. It is a crucial element not only because it is the raw-material fundament. Moreover Silicon feedstock for photovoltaic technology stands for up to 25% of direct module cost (Sarti & Einhaus 2002: 31). Hence the raw-material cost is a large input expenditure for firms. Thus a reduction of material costs could have effect of the whole value chain. Not surprising Silicon is a central focus area, not only for Norwegian companies, but for the sector as a whole. This goes for both firms and research agencies.

Silicon is the second most abundant material in the earths crust. A common presence is for example in the form of quartz (Søiland 2004: 2). Even though Silicon is a highly abundant material one starts to see signs of problems related to a lack of supply within the PV-industry (Goetzberger et al. 2003, Woditsch 2002). Why is it that the supply of an abundant material like Silicon becomes critical? The answer to this lies in the nature of the material itself, and in what ways it is produced. Silicon is not always Silicon. The critical point is that for Silicon to be of any use to the photovoltaic industry, it has to be available at a high degree of purity, which it is not in its natural presence. Thus material refinement becomes a highly central issue. Silicon has been large-scale manufactured for several decades. For one thing it was early on used as an alloy in Aluminium production. Traditional Silicon production has been done for a long period of time, and Norwegian companies like Elkem have been leading actors in this respect. This traditional production method results in metallurgical grade Silicon (MG-Si) and has a purity of 98-99%. Nevertheless this level of purity is not acceptable for photovoltaic and electronic purposes (Søiland 2004: 3). At different points in history new materials that meet the needs of new generations of technology emerge. This is the case with Silicon. In the 1950s Silicon became an important resource for the rising electronics industry. The purity requirement became an important driver and incentive for the Silicon industry to deliver products with close to 100% purity. In general 99, 9999% is the accepted and ideal purity level of the Silicon used in the electronics industry. The refinement of Silicon is a comprehensive, expensive and complicated process. The standard process which consists of a set of chemical process steps is referred to as the Siemens process. The input in this process is in fact metallurgical Silicon. The product; electronical grade Silicon is referred to as polycrystalline Silicon, or polysilicon (Søiland 2004: 3). The industry producing it is referred to as the polysilicon industry.

The microelectronics industry and the PV industry to a large extent share the material fundament, and the related technologies for production of this (Green 2000: 990). For a long period of time the source of suitable Silicon feedstock for the PV-industry has been waste and cut-offs from the electronics industry (Goetzberger et al 2003: 14). The dependence of the electronics industry has proven to be a rather risky and unstable relation, mainly because of two factors. First of all the two industries do not experience similar growth patterns. In theory this could mean that demand could override supply and vice versa. Secondly the electronics industry experiences heavy cycles of boom and depression making the supply, and price, highly unstable (Goetzberger et al 2003: 14). As an example of the effects of the fluctuations of the semiconductor markets a result was no availability of rejects, which forced companies to buy electronical grade Silicon (Goetzberger et al 2003: 14). The price of this Silicon is much higher than the rejects that usually are used. Therefore a more stable supply of specialized feedstock also would be a contributing factor to a stable PV-industry that is fast growing.

The reality has been, and is predicted to be, that Silicon of a high purity grade is an issue both for the PV-industry as well as the electronics industry. Table 3.3 depicts Silicon demand and supply of the PV and semiconductor industry. The figure shows that the Silicon demand within the PV industry is growing. At the same time the total Silicon supply is increasing at a low rate, while the rate of Silicon shortage is increasing drastically. This reflects the present status of Silicon shortage within the PV industry. It is argued that this shortage is triggered by the extreme high growth rates of the PV-industry (Jäger-Waldau 2006: 1922). Nevertheless the present shortage situation could possibly be rendered with new Silicon production plants being established in the future. While long relying on material stemming from the electronics industry the challenge in recent years for the photovoltaic industry has been to have access to sufficient amounts of Silicon of a purity grade that is acceptable for usage. Therefore a dedicated Silicon feedstock production specialized for photovoltaic purposes is crucial for future development.

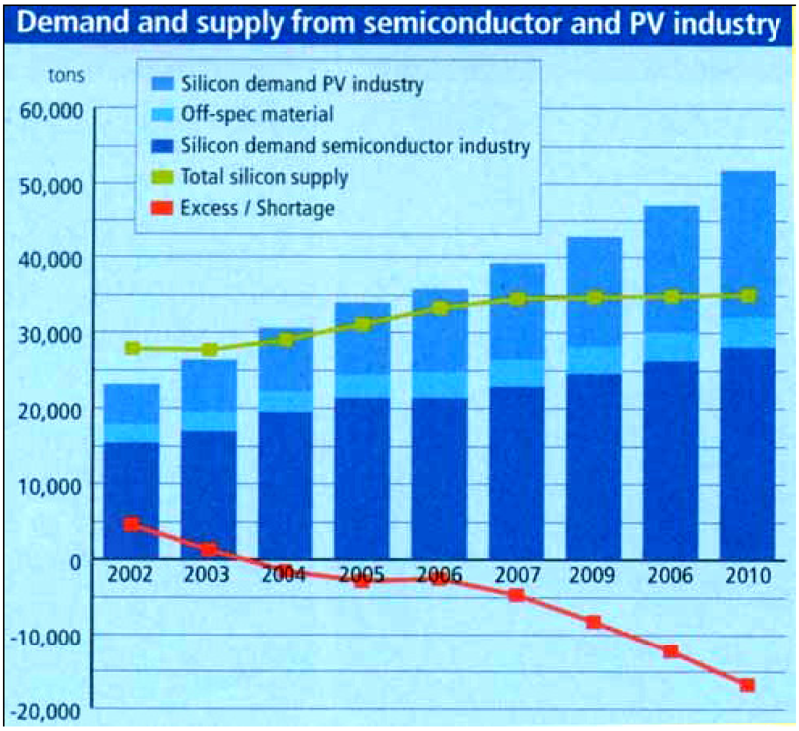

Table 3.3: Evolution of demand and supply from semiconductor and PV industry

There is an ongoing discussion in several forums concerning the importance of and possible shortage of Silicon. Many point to this shortage as being a possible “bottleneck” for growth in the industry in general. A bottleneck is in the innovation literature (Fagerberg 2005, Hughes 1983) referred to as the lack of a critical component within a dynamic system. In this specific case there is not a lack as such of Silicon as a component. More so there is a lack of sufficient amounts of suitable material. The lack of sufficient amounts of Silicon is in this paper viewed as a "bottleneck" in that it is a component of the technological or sectoral system that slows down the growth of the entire system. Both firms[7] and theorists (Goetzberger 2003) refer to the Silicon shortage as the challenge for the industry. Prices of Silicon have until now been on a high level, much due to high production cost related to achieving high grades of purity. Nevertheless the high prices of Silicon and the costly production process influence the cost of PV-technology in general. In the sector as a whole incremental improvement are important for lowering the price of the end product. The production of Silicon is the first and a very critical step in the way to make solar technology competitive.

A central issue of this paper is therefore to describe how this bottleneck is overcome. The most promising way is also one that is being pursued presently, namely the production of so called solar grade Silicon (SoG). Such a production of specialized Silicon feedstock for the PV-industry could alter the picture seen in recent years. The characteristics of which purity degree and standards such a specialized Silicon feedstock should have is a highly discussed topic both in research environments and amongst producers. There is no certain characterization data available concerning the relation of the purity of Silicon and the effect of the end product, the solar cell. What is known is that Solar grade Silicon should fill the gap between Metallurgical grade Silicon and Electronical grade Silicon, both in relation to purity and price (Søiland 2004: 3). The purity requirement is less than that of the electronics industry (Miles 2006: 1092). As will be shown; there are more than one way to overcome this

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[7] REC interview

bottleneck. Because of multiple production methods for the refining of Silicon, firms choose different strategies, that I argue are determined by path dependency.

Before moving on it is important to distinguish between the production and refining of Silicon feedstock and the further production of Silicon to be used in wafers. The Silicon feedstock of a suitable purity grade is melted into so-called ingots in specialized furnaces. After melting the next step is cooling. The finished Silicon block is referred to as an ingot. These ingots can be of different sizes. The cooling of the molten Silicon is a process where crystallization takes place. The industry in Norway is focused on so-called crystalline wafer production, either in its mono- or multicrystalline form. Furthermore there are different crystallization methods, resulting in different types of material. One mode of production that is deployed by REC[8] is the cooling of the Silicon from the bottom up. This production method results in so-called multicrystalline Silicon.

3.5.2 Wafers:

The levels of the value chain are as mentioned interlinked, which means that they are largely dependent on each other. Silicon production is for instance highly linked to wafer production. The quality of the wafers to a large extent rest on the crystallization processes of the Silicon. Based on the crystallization process there exists a technological heterogeneity of different types of wafers. In Norway single- and multicrystalline wafers are produced with a predominance of multicrystalline wafers.

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[8] http://recgroup.com/

Wafers are thin slices of Silicon sawn out of the Silicon ingot. The Silicon wafers are the fundamental part of the last step in the value chain, namely the assembly of finished modules. A central issue concerning these wafers is thinness. Given the high cost of Silicon, an important measure taken is therefore the sawing of wafers into as thin units as possibly. The driving factor behind this is of course the thought of utilizing as little as possible of costly Silicon. An additional important issue is how much Silicon that is lost during the sawing process. It is therefore crucial to minimize the Silicon wasted in dust during sawing. As will be described further on this is one important level where innovation processes are important.

An important point to be made is that 50% of the cost of a finished module is due to the cost of processed Silicon wafers (Goetzberger et al 2003: 14). The processes of manufacturing Silicon and wafers thereby stand for half the cost of a finished module. These two levels of the value chain are defined as upstream products. It is also along these two levels that the Norwegian part of the sector is focused. This means that these companies are present in a market segment were economization potentially has a large impact. The innovation processes to be described are to large extent processes of increasing cost-effectiveness. Hence following this general technological description were the technological nature of the different levels of the PV-technology value chain have been analysed a more detailed analysis of innovation processes is due. The material will build upon the technological descriptions given in this chapter and intends to give a more in depth explanation of the nature of the Norwegian sector, and seek to address why it is focused on these upstream products.

3.5.3 Modules:

The assembly of finished modules is the last step of the production process. Here wafers are manufactured into units of different size, scale and design to meet the needs of users. The wafers that have been texture treated chemically now become assembled into usable entities. A central issue is the design and how it is fitted to usage. Although modules are produced in the Norwegian PV-industry, this is not a focus area for the organizations within the innovation system. Therefore weight will be put on the innovation processes related to the two first levels of the value chain. This is not intended to undermine the importance of the last level, but is a natural choice based on the characteristic of the Norwegian industry.

Chapter 4

4 The Systemic Nature of Innovation:

An understanding of technology development and innovation processes leads to an understanding of the contribution of the Norwegian industry related to economization of processes, which is a key factor to increased diffusion of the technology. This chapter intends to show how various innovation processes increase economization and thereby increase technological diffusion.

Kline & Rosenberg (1986) point toward the importance of not viewing innovation as a simple linear process spanning from research and development to market application. Innovation should rather be viewed as a highly complex and sometimes almost invisible process. Invisible in the sense that what is often seen as a single innovation in fact consists of several small, intangible innovations. It is therefore important to underline that PV-technology is not a single innovation, but consists of numerous and equally important steps descried above. Small incremental steps and numerous processes in this context stand for a decisive economization of production.

Furthermore; firms operate and exist within a context and do not innovate in isolation (Edquist 2005: 182). This notion has inspired a systemic approach to innovation that analyses economic and technical change as existing within a broader context (Carlsson et al. 2002: 233). An innovation system is comprised of a set of organizations and institutions. Organizations are formal structures such as firms or research organizations, while institutions are norms, rules, routines and established practises that regulate the interactions among the organizations within the system (Edquist 2005: 188). A set of systemic approaches exist at different levels of aggregation, and can be delineated from a national, regional, sectoral or technological perspective (Carlsson et al. 2002: 233). Following Edquist (2005) I will in this paper use the systems of innovation (SI) concept as a wide and open approach, including both process and product innovations. Important issues regarding the SI concept to be elaborated on in the following are the role of knowledge and learning and the role of organizations and institutions.

This chapter intends to give an overview of central technological developments and innovation processes related to the technological foundations presented above. The central issue of this chapter is to point out that a new combination of separate existing entities can arise to something new. The PV-industry in Norway is here argued to have origins related to the exploitation and manufacturing of natural resources, especially the Silicon industry, both in technological and systemic sense. Aluminium and Silicon[9] have been produced for a long time in Norway. The historical linkages to this production can be said to be of importance for the innovations brought forth by the companies producing PV-technology presented in this study. This is much because of the knowledge bases that seem to be embedded within actors innovating in the industry. At the same time new kinds of knowledge are needed and are sought outside of the national system. The PV-industry sector has provided much of this knowledge. This gives rise to the assumption that different systemic contexts interact and are important for the establishment of this industry in Norway.

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[9] Aluminium and Silicon to some extent share production methods. Additionally Silicon is used as an alloy in Aluminium production. Parts of Elkem`s Metallurgical Silicon is used for this purpose.

The chapter will argue that an understanding of the different levels of systemic aggregation as interacting is fruitful. The levels of aggregation do not have to be seen as conflicting, but rather as complementing. I will use the SI approach on both the sectoral as well as the national level of analysis, to portray interactions amongst the two systems. Segments of a sectoral system of innovation (SIS) in some way or another have relations to their respective national system of innovation (NIS). Following Malerba (2004) the characteristics of the national system influence the features of the sectoral system. Important elements of the national system that are seen as influential are institutions and policies of a national character that determine behaviour of the organizations within the system. The national system can be seen as a contextual frame into which sectoral systems are embedded. Any given part of a sectoral innovation system does belong to some national system. Furthermore a sector can cross national boundaries, at the same time as the different actors within the sector all have national links and connections. In this case the national influence on the industry is seen primarily on the setup of mode of production. I argue that the focus on upstream levels of production is explained by path dependency issues related to the NIS. The sectoral composition and mode of production of the PV-industry is therefore argued to be influenced by paths and trajectories originating within the national system. At the same time knowledge and technology transfer with origins in SIS are highly central. Therefore the sectoral composition, and eventual changes, also affects the national system. The PV-industry is therefore seen as having strong linkages to both the sectoral, as well as the national system of innovation.

The Norwegian PV-industry consists of several actors producing elements of the value chain for photovoltaic technology. In figure 4.1 the three main technological levels described previously; silicon, wafers and modules, are linked to the organizations within the sectoral system. The figure displays the central organizations in Norway and shows that all producing organizations are related to Silicon production. REC and its subsidiaries are the only producers of wafers and modules in Norway, but are at the same time well established within this field. They are also the largest company globally producing all elements of the value chain. The research organizations within the system are to a large extent focused on Silicon and wafer technology. Hence a concentration and focus on upstream elements; Silicon feedstock, ingots and wafers is seen in the Norwegian part of the sector. This is the case presently, and especially so historically.

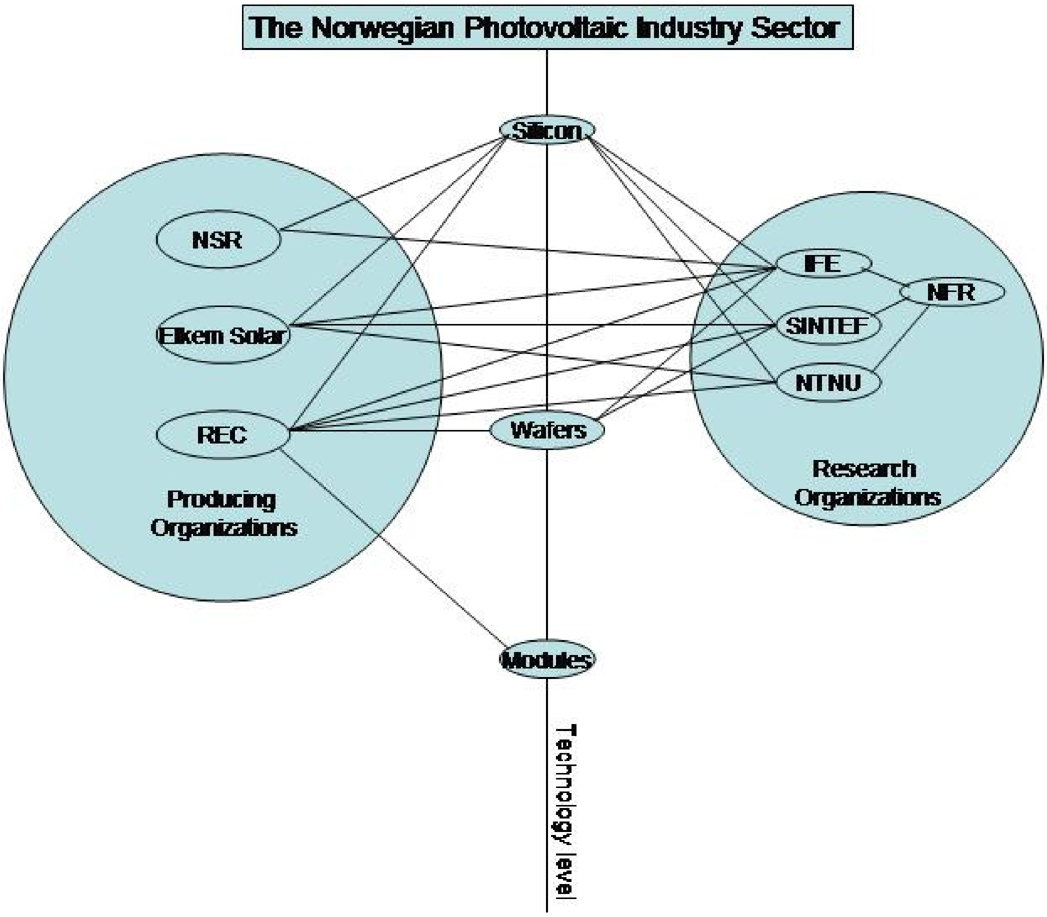

Figure 4.1: The Norwegian Photovoltaic Industry Sector

4.1 Innovation Phases:

In this chapter the establishment of the PV-industry in Norway and its related innovation processes are divided into three separate yet interlinked phases. The paper therefore analyses the establishment at three levels; the pre-production phase, the establishing phase and the momentum phase. These phases must not be viewed rigidly or separately. Rather they are used as a structuring tool to portray the complex reality of innovation processes. The passage from one phase to another is seen as a sliding transition, where a new phase is seen as an additional new layer. The new phase or layer contributes with new knowledge bases, production activities and technological and institutional change that arises gradually.

Phase I is a *pre-production phase,* where no actual production of PV technology has been established. This phase is characterized by two central factors; first by the construction of knowledge bases and the related learning processes, and second by the explorative and seeking activities both research- and market-wise. These two factors are seen as interlinked in that the explorative activities broaden knowledge bases. It is important to emphasise that the knowledge foundations created in the pre-production phase are of high importance for the next phases, which therefore can be seen as standing on the shoulders of the first. Phase II, the *establishing phase* is first of all characterized by industrial structuring, mainly because of the start-up of the company Scanwafer, that started production of Silicon wafers. Furthermore the phase is characterized by a widening of the NIS, and a deepening of the SIS. A dynamic interaction can be seen here in relation to the different forms of knowledge existing in, and interacting between the two innovation systems. Regarding the NIS, the establishing of the industry gives rise to a widening of the existing structures with the advent of new technological foundations, new knowledge bases and learning processes. The deepening of the SIS takes place through the contribution of incremental innovations provided by the establishing Norwegian PV-industry. Through the establishing of the industry new players and new dynamics enter the sector. This phase is also characterized by a more structured appearance and, with new characteristics of the institutional set-up arising in the NIS. Phase III, the *momentum phase* is characterized by settled and more structured organizations embedded both in the NIS and the SIS. Furthermore the widening of the NIS and the deepening of the SIS is becoming more concrete, at the same time as the systemic interaction gives rise to technological and institutional change within the NIS. A continuum concerning cost reduction and incremental process innovations is seen. Furthermore a focus on Silicon feedstock becomes more apparent. At the same time production becomes increasingly industrialized.

Innovation Phase	***Characteristic***
Phase I - pre-production	Unstructured, exploring, learning
Phase II - establishing	Structuring, incremental innovation
Phase III - momentum	Structured, increasing size, incremental innovation

Box 4.1 – Development phases of the Norwegian PV-industry

The empirical material to be presented is organized around the above mentioned phases, and is linked to theoretical topics. I remind that these phases must not be seen as distinct and demarcated categories, but rather as sliding transitions with changing characteristics. Such a distinction into phases makes it more feasible to discuss the systemic innovation activities at different levels. As will be seen; the core activities within the sector are changing in nature as transition between phases takes place. This affects both the structure of the innovation system as well as the elements that constitute the system.

4.2 Phase I: The Pre-production Phase - Origins of the Photovoltaic Industry in Norway:

History matters. This is arguably so when analyzing knowledge bases while studying the development of the PV-industry. It is therefore a necessity to start telling the story at a point in history where no actual production of PV-technology was established. The pre-production phase has been highly important in providing knowledge bases for future developments. This first phase is characterized by unstructured explorative actions. In addition, even if there are no direct causal links, the industrial activities of this phase have in retrospect proven to be highly essential for development in the future, particularly in the field of Silicon production. Again the innovation time span is important to point out. The material presented in this chapter shows that not only the innovation cycle of photovoltaic technology is long, but that the innovation processes for Norwegian firms wishing to enter this industry have been time-consuming.

4.2.1 The Chemical Process Industry and Silicon:

The central role of Silicon cannot be analysed without going further back in history. A central argument of this paper is that innovation in this industry is contextual and path dependent. Therefore the traces and ties to the Silicon industry must be explained. Furthermore it is important to shed light on the endeavours of the Silicon industry to attain high purity levels of this material.

When addressing why the photovoltaic industry has been established in Norway and why it is preoccupied with the production of upstream products a central starting point is looking at background issues. Pavitt (2005) states that manufacturing firms are highly path dependent, which in short means that what firms do in the future depends on what is learned in the past. Taking this point into consideration looking at the relations between the chemical process industry and the PV-industry is fruitful. Elkem has long been a central actor within the process industry. A look at what Elkem has done in the past will show that not only has the company built up important knowledge bases related to Silicon production in the pre-production phase, but has also been a contributor to the establishment of the PV-industry along the way in different forms and shapes.

Elkem is one of the largest industrial actors in Norway as well as globally within the chemical process industry. The company specializes in metallurgical processes, and has existed during the whole last century. Throughout the years the company has worked up a strong knowledge base related to working of melting furnaces, and Silicon production in general. I argue that being a large actor within the process industry, Elkem also has strong ties to today's PV-industry in Norway. Not only because the company aspires to produce Silicon for the PV-industry, but also because early foundations for the establishment of the PV-industry were laid within Elkem. The links between Elkem and the PV-industry actually can be drawn a century back in time when taking a broad look at what can be referred to as "industrial knowledge". The knowledge bases related to the refining of natural resources began to grow in Elkem with an interest in iron ore deposits. This was in the early 1900s. After World War II the links become more evident, as Elkem started production and export of Aluminium, Ferro alignments and most importantly Silicon (Sogner 2003: 9).

When discussing Silicon specifically it is important to note that the development towards a production of refined Silicon first of all has gone through various stages, and has included various actors. Moreover it must be reminded that various levels of Silicon qualities exist, which are used for different purposes. Elkem has throughout the years focused on, and has also been the world's largest exporter of Metallurgical grade Silicon. This has been a central resource for the *polysilicon* industry which is the industry that further has refined the Silicon, to be used particularly by the electronics industry. This means that Elkem did not deliver materials directly to the electronics industry, but that the polysilicon industry was a connecting link which proved to be of importance for future developments[10]. The relation of raw-material fundament between the electronics industry and PV-industry has been elaborated previously, and it is important to remind that the two industries for a long time shared this fundament, and moreover the requirements of Silicon of a higher purity degree.

The wish to attain Silicon of higher purity levels has been important throughout the years in Elkem, and can be seen as a central activity in finding new business areas. An important step was the introduction of the special quality Silicon referred to as *Silgrain*. This product was delivered to the polysilicon industry, which given the higher purity level the product gave the polysilicon industry especially good results. A set of important process developments took place which resulted in the establishment of a plant in Bremanger that produced Silgrain. This was sold globally. This is referred to as the first innovative step that led Elkem to establish tighter bonds with the polysilicon industry. These bonds have been important for the further developments, and were particularly essential in that it led Elkem to establish important relations to the electronics industry through the polysilicon industry. To a large extent the background for developments of higher purity Silicon was an understanding of a demand of

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[10] Elkem Solar Interview

the industry for Silicon of a higher purity grade[11]. By and large it can be stated that Elkem has sought processes with which Silicon can be produced at a higher level of purity. For a long period of time this demand came from the electronics industry, through the polysilicon industry.

The goal during these years has been the development of a process technology which purifies Silicon in a simple, cost-effective and energy saving manner. In Norway this was solely a goal of Elkem.[12] It is argued this is due to size and finance situation of the company. In retrospect it can be stated that it has been acknowledged that processes used in the polysilicon industry are expensive and energy demanding. At the same time one has aspired to improve products. This has been to serve the polysilicon industry, as well as seeking out new processes. To skip the step of the polysilicon processes then would be both cost and energy diminishing. Such endeavours have been ongoing in Kristiansand since the 1980ies. The environment around "Elkem Research" has been a hot tub for these developments. Groups of researchers, in specially built laboratories with testing furnaces worked for long periods of time to find new solutions to processes with which Silicon could be produced. In addition projects with the electronics industry were pursued, which later have been followed by projects with the PV-industry. Moreover there are important links to key organizations within the national innovation system like Norwegian Institute of Technology[13] and SINTEF[14]. As mentioned the research environment was centred on finding new, and more efficient refining processes, as well as improving existing processes. A central element of the Silicon production process is the melting furnace. The knowledge related to these furnaces to a large extent has been acquired through experimental learning processes (Sogner 2003: 290). Or in Lundvall`s

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[11] Elkem Solar Interview

[12] Elkem Solar Interview

[13] Norges Tekniske Høgskole (NTH) was until 1996 the predecessor of NTNU.

[14] The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology

(1992) terms, processes focused on learning by doing. Nevertheless the developments of finding new processes also showed the need for science based knowledge. At this stage the integration of scientific knowledge into the production became important, and a more systemic mapping and scientific understanding of what goes on inside a melting furnace has been pursued since the early 90ies. This shows not only the need for various competences, but also the importance of the NIS in providing such elements. An incentive for these developments was the potential of cost reduction, which by then was believed to be achieved by the enhancements of production processes. In this development the ties between Elkem and important technical research environments such as NTH / SINTEF become more evident. For instance the establishment of "Elkem University" in 1991, where a forum for discussion and learning of metallurgical core processes was founded, was a central effort to combine internal and external knowledge (Sogner 2003: 293). Moreover such important elements of the institutional setup within the national system, proved to be essential for increased scientific knowledge of melting furnace technology for implementing new processes.

Elkem was also involved and related to the PV-industry early on through these materials[15]. This meant that Elkem knew and understood the demands of the PV-industry. The above mentioned can be seen as a starting point for comprehensive innovations in Kristiansand environment, that now are the foundations for Elkem Solar, which now intends to produce Silicon feedstock specifically for the PV-industry.

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[15] Elkem Solar Interview

4.2.2 Exploring Activities:

A part of the characteristics of the pre-production phase are the explorative activities. Much of these explorative activities can be related to the networks that were established with the polysilicon and electronics industry, and later with firms in the PV-industry. In this phase a sectoral systemic composition in Norway is in the making. Therefore the early activities can be seen as unstructured but constructive rather than systemically mature. This is reflected in that Elkem was the only organization actively affiliated with photovoltaic technology. During the 80ies Elkem was looking at opportunities within the field of solar energy. In this period the economy of the company was strong, and allowed expansion and new thinking related to new business opportunities. The processes that characterized this were both technological change within the existing foundations of the company, such as seeking new Silicon refinement processes, at the same time as acquisitions were made to further enhance Elkem`s standing within the industry. The technological changes during this period can broadly be defined as improvements in Silicon refining processes. The development of Silgrain was for instance an important technological change. A part of the efforts to further gain a position within the photovoltaic technology was the acquisition of existing companies. This acquisition in companies of technological relevance can be seen as a part of a process and linked to technological change. In the early 90s Elkem had a tight cooperation with an unnamed large American company, were testing of the production of PV-technology out of Elkem material was done. One was far away of having the necessary raw-material specifications, volumes and business plans, but nevertheless showed the potential and possibility[16]. These first explorations into new business opportunities were going to be important not only for the company but for the industry in Norway as whole. Through these

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[16] Elkem Solar Interview

explorative activities Elkem got to know the business, and also had ownerships in companies of significant size. Amongst others the British company Crystallox was bought in 1985 (Sogner 2003: 271). In this case the acquisition can be seen as a strategic attempt at securing technological know-how and competence. The company was bought with the background in interest in diversifying Silicon production, and seeking out new target markets. Crystallox was a leading producer of crystallization furnaces. At Crystallox detailed plans for wafer production were developed. Nevertheless, Elkem experienced a financially complicated period in the early 90ies, and as part of company restructuring and cut-backs the decision was made to sell Crystallox in 1993 (Sogner 2003: 289). This sale also marks a period of time were the activities related to PV-technology were put on hold. Elkem had aspirations and goals of partaking in the PV-industry since the early 80ies[17]. Hence the above mentioned points out an interest of the company in PV-technology, but was for several reasons, especially economic, not carried out to full potential at this point. This was no focused activity until 2001 when Elkem Solar was established.

The above mentioned points towards the importance of knowledge bases both within the NIS and the SIS. In phase I the interactions are not very evident because they were fragmented and unstructured, but two central general factors are evident. First, as mentioned, the important foundations lying in the long history of Silicon production at Elkem must be emphasised. The existing knowledge related to Silicon must be acknowledged as an important part of knowledge resources. Furthermore path dependency related to innovative activities is identified. Second, and linked to the first, the network that was built, although unstructured, proved to be important for future developments. This network was established trough the existing network within the Silicon industry. In this early phase Elkem was an important

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[17] Elkem Solar Interview

driver. The national systemic properties were at this point weak, but the institutional setup involving Elkem and NTH/SINTEF must be acknowledged as an important early driver.

4.3 Phase II: The Establishing Phase - Rupture and Continuity:

Given the above mentioned, technology and knowledge related to Silicon production was not something to come from out of nowhere. Innovation is contextual and cumulative. The foundations laid in the pre-production phase are therefore seen as central for the further developments. Phase II is therefore a continuum of phase I in that it rests on its foundations. Nevertheless, the technological focus in the establishing phase is on wafer production. The production of Silicon raw-material first becomes an increasingly central issue in the third phase.

With the establishing of the PV-industry in Norway a widening of the NIS takes place. This widening takes place with new technological foundations and knowledge bases entering the system, due to interactions with the SIS. Furthermore the links to, and networks within, the SIS established in the pre-production phase are of continued importance. The interaction between the two innovation systems increases at this stage. Important points of systemic interactions are here identified not only in knowledge flows between the systems, but also in the clearer manifestations of markets, which are global.

4.3.1 Rising out of Existing Structures:

As mentioned, Elkem experienced financial challenges and needed public refinancing in the early 90ies. The main reasons for these financial problems were the crisis stricken steel markets on a global scale, which directly affected business activities of Elkem. During this period anything that was not seen as a core business was sold. Hence the basis for doing R&D on anything not related to core business also was non-existent. This meant that research and development related to PV-technology was not prioritized within the company. Nevertheless, much of the staff, knowledge and competence related to PV-technology survived this troublesome period[18]. During this period Alf Bjørseth was R&D director at Elkem. Through this position he was an important part of the projects and groups related to Silicon that had run from the early 80ies. The main field of work here was related to finding processes for Silicon purification (Ruud & Mosvold Larsen 2005: 21). Not only was the relation to work related to specific Silicon technologies important in this context, the knowledge and relation to industrial communities and networks, such as companies like Crystallox, was of equal importance. During this period Alf Bjørseth recognized the business opportunity in the production of Silicon wafers, and suggested the production of such wafers to Elkem`s management. These plans were the ones developed at Crystallox where Alf Bjørseth was chairman of the company after the acquisition (Ruud & Mosvold Larsen 2005: 21). The suggestion was made well knowing that Elkem did not have raw materials of the right quality themselves. Even though Silgrain was a product with a high purity degree, it was not developed directly for this purpose, and was not sufficient as feedstock for PV-technology production. Bjørseth`s suggestion to the management was buying material scrap and rejects from the electronics industry, as was done by other companies within the industry. Due to the

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[18] Elkem Solar Interview

fact that Elkem recently had been through a troublesome period Bjørseth`s suggestion was not followed up on. The instability and risk seen within the solar cell industry are other important factors behind this hesitance. The unwillingness of Elkem at this point at the one hand, and his own belief in the potential within the PV-industry at the other led Bjørseth to decide to follow up on the plans separately of Elkem. This rupture is seen as the starting point for Scanwafer. Nevertheless the links to Elkem were not cut off. Elkem was in with 10% ownership. Furthermore contact especially through R&D collaborations was also continued to some extent.

4.3.2 Financing of Production Start:

After leaving Elkem Bjørseth was in need of finding financing partners for the establishment of the first production plant. The first endeavours outside of Elkem where pursued together with Reidar Langmo of Meløy Næringsutvikling[19] with whom he established Scanwafer (Ruud & Mosvold Larsen 2005: 21). The main motivation behind the start-up is argued to be the belief that the solar energy sector was growing and that a location in Norway had a large potential. The potential of locating the industry in Norway is related to both infrastructure, societal and knowledge issues. According to Wicken (2005) an industrial infrastructure in decentralised areas of Norway has been central for industrial developments, and has existed for over a century. It is pointed out infrastructure was one central issue behind the choice of establishing Scanwafers first plants in Norway.[20] The infrastructure consisted not only of production facilities but also access to cheap power and cooling water. A large amount of energy is required in the melting of Silicon into ingots, and also in the further production

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[19] Meløy Municpality office for industrial and commercial development

[20] REC Interview

steps. Therefore access to reasonably priced power was of crucial importance.[21] Access to power was secured by a reasonable deal with Hydro Energi, which had a close relationship with Meløy Næringsutvikling. This was a key factor that contributed to making Glomfjord an optimal location for establishing the industry (Ruud & Mosvold Larsen 2005: 25). Additionally vast amounts of cooling water are needed in relation to the melting processes. The coastal location of production facilities is therefore an important factor.[22] The first production facilities that were taken over from Hydro in Glomfjord proved to be highly suitable both related to access to reasonable power, and access to cooling water. Another key factor concerning production start-up was taking over a group of skilled workforce. Sources at REC point out that having a workforce familiar with the process industry was of high importance. A part of the deal of overtaking Norsk Hydro`s production facilities was also retraining of the employees. This first of all points towards the essential role played by a competent workforce. Secondly the re-education of workers had a relation to Norwegian regional policy, in that this retraining was supported by the public.

The financing of the first plant at Glomfjord came from several different sources, both private investors and public funding. Norsk Hydro was not only important by providing production facilities and workforce. They also played a part in the financing of Scanwafer. Meløy Næringsutvikling was partly owned by Norsk Hydro, and can be seen as part of an effort to stimulate new industrial development. This was the will of Hydro due to its downscaling. Furthermore SND[23] (Norwegian Industrial and Regional Fund) and local banks were important at the financing level of the innovation process. SND was willing to support 25%[24] of the estimated total investment. In providing this support SND demanded documentation of

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[21] REC Interview
[22] REC Interview
[23] SND has in recent years become a part of Innovation Norway, which also has regional development offices.
[24] This is estimated to be 70mill NOK.(Ruud & Mosvold Larsen 2005)

existing markets for the products, as well as the support was given on conditions of a bank loan. Before production was started sales contracts were signed for the four first years of production. These contracts were made with European companies, Neste Advanced Power Systems (NAPS) being the most important. The sales contracts were the decisive factor that convinced SND to provide funding. At the same time the funding convinced banks to provide loans (Ruud & Mosvold Larsen 2005: 22). Elkem also contributed with 10%[25]. The first production at the Glomfjord plant started in June 1997.

In the above mentioned the role of the national system becomes more directly evident than in phase I. First of all the industrial facilities and workers that played a key role in making the establishment possible can be said to be a part of the national system. Furthermore what I refer to as “industrial knowledge” also is a key factor. This knowledge can be seen both in the competent workforce that is necessary, and the network context the founders of the company were operating within. Lundvalls (1992) terms *know-how*, and *know-who* are descriptive of these types of knowledge. Practical know-how both among workers and the management was essential. In addition the know-who of the founders seems highly important in the early establishing phase. The networks and knowledge of the networks was something that did play a major role, not only in relation to the sectoral system, but also to the national. Whereas know-who of important actors in relation to infrastructure and funding was important in the NIS, the know-who of market relations existing was an important factor in the SIS. A point where systemic interaction is clearly identified is therefore in the relation between funding and markets. At this point the interaction between NIS and the SIS was of significant importance. This also provides evidence for the interdependence of the two systems. Were at the one hand Scanwafer was depending on funding within the national system, the market for

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[25] Elkem Interview

the products on the other hand existed in Europe amongst companies in the sectoral system, outside of the national context. Therefore the establishment of Scanwafer has a background in both systems, with both systems contributing with important drivers for innovation.

4.3.3 Knowledge Transfer and Competence Acquisition:

Regarding knowledge, it was not only important to have a competent workforce for production of wafers, but also the acquisition of knowledge and know-how for building up of production facilities. Here ties back to Elkem can again be drawn. First of all Bjørseth took with him a great deal of colleagues from Elkem to fill important positions. Additionally contact with the formerly Elkem owned company Crystallox was pursued. Dr. David Hukin, founder of Crystallox, was a key actor as technical consultant during the establishment of the first factory in Glomfjord (Ruud & Mosvold Larsen 2005: 21).. His speciality during this development was crystallization processes. Although the furnaces were bought from Germany, his knowledge of crystallization processes was a key factor. The crystallization processes are as mentioned an important step in the Silicon production stage, and is critical for wafer quality. This is seen as an important instance of technology and knowledge transfer into the national context with origins in the sectoral system.

4.3.4 Learning and Process Innovation:

The knowledge that is integrated during the establishment phase is based on different learning processes. One such learning process is user-producer interaction, which will be discussed in the next section. First it is important to look at how learning processes relate to process innovation. The innovations seen in the Norwegian part of the sector are seen as incremental, spanning over rather long periods of time, and are experience-based rather than radical innovations. The innovations put forth first by Scanwafer, and later by REC, have been process, not product innovations. The product and technology existed for several years before the production at Scanwafer started. Moreover it can be argued that while being a radical innovation within the Norwegian national context, the process innovations can be seen as incremental within the sectoral system, whereas the innovations can be viewed as radical to the extent that they have contributed to heterogeneity within the Norwegian economy. In the case of the PV-industry in Norway the process cannot be seen as a linear process with clear-cut steps of research and commercialization. Rather the many steps are interlinked and take twists and turns in different directions.

Lundvall (1992) proposes that while science and R&D do matter for innovation processes, other input factors also are of importance. Being a proponent for the importance of learning, the importance of learning processes related to routine activities such as production, distribution and consumption are emphasized. The importance of such learning also becomes evident in the case of the empirical evidence provided by the firms in this paper. It can be argued that in the case of Scanwafer, and later regarding REC, the process innovations that have taken place in this firm could be described to a large extent as being a combination of science and R&D efforts, and various forms of learning and competence building related to the production process. There are several important learning processes that can be identified in the case of REC. First of all, the establishment of the first production facility in Glomfjord was a process where the combination of scientific knowledge, industrial know-how and a highly qualified workforce was essential. Second the acquisition and development of new technological solutions involve a high degree of learning. The company has modified processes throughout the years to meet higher demands of the market, at the same time as these processes have become increasingly cost-effective.

These process innovations can be said to have a background in the sectoral dynamics. The criticality of Silicon can be said to have direct influence on the incremental process innovations done related to wafer technology at Scanwafer/REC. As mentioned; the high growth rates in PV technology seen in recent years have led to decrease in the availability of Silicon raw-materials (Jäger-Waldau 2006: 1). The criticality of access to Silicon raw-materials has been referred to as a bottleneck by the industry[26] and also by theorists (Jäger-Waldau 2006: 1). The most important innovations done by REC are technological developments that increase and better the utilization of Silicon. These innovations also are closely related to an increase of cost-efficiency in all levels of the value chain.

4.3.5 Technological User-producer Interactions and Technology Transfer:

In this section I will look closer at two cases of user-producer interaction of high importance for the establishment of the industry. Among the important relationship in an innovation system, technology transfer is central. The two examples can be seen as instances of interaction between different knowledge bases, as well as the interaction between two innovation systems. Hence it can be said that the systemic interaction with a base in knowledge flows, and technology transfer takes place in these user-producer interactions.

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[26] Interviews REC, NSR

The technological developments related to wafer production in the Norwegian PV-industry can be said to be done mostly by Scanwafer, and later REC, at least when it comes to commercially available products. During start-up of the first Scanwafer plant in Glomfjord several factors were of importance. At the one hand financing was important to get things going, at the other hand the technological basis on which production was to rely was of equal importance. Technology development was a core activity of Scanwafer. Technically speaking the most important innovation processes for REC were related to the crystallization furnace and a specialized wafer saw (Ruud & Mosvold Larsen 2005: 22). At that point in time two or three technology suppliers delivering the technology needed for wafer production were available. These two innovations can be seen as important incremental process innovations contributing to a development of a more cost-effective production process in general.

4.3.5.1 Crystallization furnace:

An important early step in the production process is as mentioned the crystallization of Silicon, which is done in furnaces. The crystallization furnaces used in the first Scanwafer plants were produced in cooperation with the German company ALD. This company is specialized in vacuum process technology, and produces amongst other products a vacuum furnace. The technology is modular, and therefore is highly adaptive[27]. The goal of this collaboration between Scanwafer and ALD was to achieve crystallization furnaces that were more efficient. This cooperation has proven to become of great importance to Scanwafers competitive advantage, and is seen as one important incremental innovation process that helps increase cost-effectiveness. It is argued that this technically speaking is the most important innovation for Scanwafer (Ruud & Mosvold Larsen 2005: 22). Theoretically speaking, this cooperation between the two firms points towards the importance of user-producer

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[27] http://www.ald-vt.com/

interactions in the innovation process. In this collaboration process both companies contributed with their knowledge and expertise. The agreement was that Scanwafer received ten years of exclusive rights for usage of the technology, in return for buying an agreed amount of furnaces.

4.3.5.2 The wafer saw:

The Silicon that is produced in the crystallization furnaces mentioned above is delivered in blocks referred to as ingots. Another crucial step in the production process is the sawing of these ingots into thin wafers. For several reasons, the price and scarcity of Silicon of acceptable purity being the most important, these wafers must be sawed as thin as possible. This is also where Scanwafer originally, and REC presently, has made important incremental innovations.

As regards wafer cutting, a specialized wire saw is the most important application. These wire saws have the ability to cut Silicon ingots in thin dimensions, making the process more cost-effective. The Silicon waste during the sawing process is a large loss in production. Therefore the sawing not only must deliver thin enough wafers, but should also contribute to that as little Silicon as possible is wasted during the sawing process. It must be noted that the development of sawing technology is not due to in-house R&D at Scanwafer. The technology was bought on the European market, where technology for wafer sawing was being produced. The saws were delivered by the Swiss company HCT[28]. This company is a recognized supplier of Silicon sawing equipment to both the semiconductor and PV-industry. Employees of Scanwafer were actively taking part in the production process of this saw, making suggestions, which resulted in a specialized type of saw for which Scanwafer now owns

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[28] http://www.hct.ch/

exclusive rights (Ruud & Mosvold Larsen 2005: 24). Information on the technological specification is not available, but the key factor here is that this collaboration is seen as efforts made to integrate new production technology as a key element in reducing costs.

On a higher level of aggregation these collaborations in furnace and sawing technology point towards several factors mattering for innovation. First of all the furnace and the saw are part of incremental process innovations that enhance the production process at different levels. Both have to do with the effective usage of Silicon raw-material, as part of efforts to reduce costs in at various stages in the production process. At the same time the furnace and the saw are a part of a total sum of innovations leading Scanwafer towards the goal of producing solar cells at lower cost levels. As mentioned, an underlying fundament for successfully achieving these innovations was the collaboration between firms. In other words a user-producer interaction among the firms was of necessity both for developing the relevant technology, and for the future competitiveness of Scanwafer. Lundvall (1992), states that such interaction is of as high importance for successful innovation, as is shown in these empirical examples. Both firms got something out of it when speaking of profit. At the same time the relatively new and young company Scanwafer had implemented a technological innovation in the process that helped them become more competitive. Furthermore it is important to note that in phase II, the establishing of the industry was dependent on the sectoral system in relation to knowledge and technology. The user-producer interactions mentioned above spanned across systemic boundaries. The sectoral system where companies both producing PV-technology and production technology existed, proved to be a systemic context within which the emerging PV-industry in Norway found crucial elements.

4.4 Phase III: The Momentum Phase – Increasing Size:

Phase III can be said to be characterized by structured companies of a large size acting within a global sector. This is particularly so with REC. In this phase incremental innovation is still important, but some of the technological challenges mentioned previously become more clearly defined, as well as they are more clearly addressed. These challenges are common to the whole sector, and one particularly important is related to the Silicon feedstock issues mentioned previously. Thus the focus on upstream products is upheld, and more concretely focused in phase III. REC is the only company producing technology along the whole value chain, but is focusing its efforts on upstream products; Silicon feedstock and wafers. This is seen in the investment focus and strategic decisions of the company[29]. Moreover the focus on upstream products is strengthened with the entering of new firms at the upstream level of production. As will be shown, when both the technology and the companies become more mature, the feedstock issues are addressed differently. All three companies analysed in this paper are preoccupied with addressing the feedstock issues, with different approaches. Furthermore, the production method that is chosen to a large extent depends on learning processes and knowledge bases that are path dependent.

I argue that the technology in this phase has become increasingly embedded nationally. By this I mean that, given the systemic interactions discussed previously, an increase in systemic elements of the national system are preoccupied with activities related to the PV-industry. In such cases the input from the SIS is seen as decisive factor generating technological and institutional change within the national system. Markets still exist overseas, but important changes regarding research funding and the institutional setup is taking place. For instance

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[29] Solar-powered growth; Annual report 2004 Renewable Energy Corporation

research networks working closely with the industry on concrete projects related to PV-technology are established. These networks are argued to be continuing from those seen in the two former phases, but are more defined and embedded.

4.4.1 Competition and the Securing of Silicon feedstock: Three Companies and Three Processes:

In the third phase organizational and institutional change is more evident than in the two first. These changes are important to describe because much of these changes are highly related to Silicon feedstock issues and upstream activities. There are several ways with which the Silicon bottleneck can be addressed. One is as mentioned the improvement of existing production processes to lower the input and waste amount of Silicon. Such endeavours have been important for Scanwafer. An application like the wire saw mentioned above is important in this respect. Yet such measures are not sufficient given the growth of the industry. Another, and of course a complementing way is to increase the amount of Silicon available. This is one central focus area of the companies within the Norwegian industry. As mentioned the largest supplier of Silicon until recent years was the electronics industry. The cut-offs and rejects from this industry has provided the PV-industry with feedstock, but this has been a complicated relation. As mentioned the availability of Silicon raw material for the PV-industry is referred to being a bottleneck for the whole industry, and the criticality of Silicon feed-stock for the PV-industry leads to several industrial and market dynamics. This is also a point at where competition is strong, and where technological developments and innovations are important (Jäger-Waldau 2006: 1). Thus specific feedstock for the industry is needed.

As shall be seen much of the activities and behaviour of the producing organizations evolve around endeavours to reduce costs, and to find cost-effective production processes for the refinement of Silicon. It may be argued that this is the single most important issue and driver of dynamics for the industry at this point in time, as the technology is becoming more mature. The technological advancements and incremental innovations that lead firms to become more competitive, and reduce their costs are of high importance. Innovations related to Silicon refinement are of utmost importance in an industry where raw material has a high price, and where the diffusion and usage of this technology, to a large part depends on the reduction of costs.

The challenge of achieving the goal of delivering Silicon of a suitable purity grade is complex. Not only does the goal of suitable purity Silicon involve several steps, but also several different routes to achieve the goal. This is reflected both in research done within the area, as well as company strategies and choice of production method. With several available routes to achieve Solar grade Silicon (SoG), the choice of which that is the most effective is a matter of several factors, amongst them path dependency and business strategy.

- ***REC:***

As REC has grown, different learning processes can be said to have taken place. In later years learning processes are also identified more closely related to organizational issues, which again are seen as tightly related to the increased focus on industrializing. At this point important decisions such as the choice of focusing on upstream products can be tied to the learning and increased understanding of the sectoral dynamics due to presence within the sector for a period of time. Moreover this increased focus on industrializing is inherently connected to the Silicon bottleneck. As shall be seen a large part of the change in organizational structures involves inclusion of elements related to Silicon production. This focus depicts the ability of the company to identify strategic points, at the same time as it recognizes market opportunities in the upstream activities. Several developments in the company structure have changed the ways in which the company behaves. One of the most important changes was the establishment of REC as a holding company. The original company Scanwafer became a subsidiary of REC. While Scanwafer was focused on wafer production, the most important change was that REC as a holding company now had production facilities, and thereby also a closer knowledge and expertise, related to all levels of the value chain of PV-technology. This includes both the production of Silicon feedstock, and module production. This has made it possible to be present at levels, and thereby also to integrate knowledge among the different levels. In the new millennium REC has become both a multinational corporation and a shareholding company. The organizational changes can be seen as a comparative advantage in itself, and strategic work to enhance further growth of the company, with a focus on upstream products. Furthermore the organizational change has made capital available for the rather large investments needed in the focusing on these upstream products.

The criticality of Silicon raw material has been an issue early on for REC. In fact the reliable access to Silicon feedstock was a demand Scanwafer posed to REC in the merger. (Ruud & Mosvold Larsen 2005: 24). From a firm perspective the shortage of such resources could be of critical character. This is also why REC has chosen to invest at this point of the value-chain. REC now controls two Silicon production plants in the US.

For the firm Silicon becomes a critical factor when demand is exceeding production levels of wafers and modules. Silicon must therefore be seen as a factor in direct and close interplay with all other levels along the value chain. The balance among the different levels thereby is of importance to the growth of the sector.

> "The problem is that the market demands more than we can deliver. That is when Silicon starts to become a critical factor. All our clients and customers, and our competitors scream for more Silicon. We do not have any more to deliver. This is not done by just flipping the switch and start producing more".[30]

The statement refers to the interdependencies among the different levels of the value chain. The criticality of Silicon as raw material is of high importance for the rest of the value chain, but the following levels are of equal importance in that a growth in Silicon shipments in itself does not solve any problems. An important factor for any firm within a high growth sector is to grow in the right way. One discussion in the field and the industry is therefore if this has a background in the Silicon industry and the high cost, while REC for example point to that this is one important level, but that the others are of equal importance. The different levels of the value chain must grow in relation to each other. But a high demand of wafer producers has been evident the last years, which as mentioned has led to shortage. REC states they have a sufficient amount of Silicon for their own production. Given the high importance of Silicon in the production of PV-technology the securing of Silicon feedstock is a crucial strategic point for firms within the sector. Expansion plans of constructing of a new Silicon plant are further pursued. This plant has an estimated price of 600 million USD, and is going to double total Silicon production by 2008[31]. The goal of REC is to build a secure capacity. This capacity should at the same time be competitive, with a goal of reducing costs.

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[30] Thomas Fernandes; REC Project Manager

[31] Presentation of Interim Results 2nd Quarter 2006 Renewable Energy Corporation

In the production of Silicon feedstock REC relies on a production process that to a large extent has similarities to what is referred to as the Siemens process, that involve gas phase production steps. The two Silicon plants bought in the US produce Silane gas that is solidified in the following steps. Nevertheless this is but one way to produce feedstock, as shall be seen in the following different solutions exist, and are pursued industrially.

The organizational change to a bigger holding company has increased the capital within the company. This has made strategic investments possible. In relation to the challenges posed by technological heterogeneity presented above, REC has since 1994 owned a 23% market share of the German company CSG Solar AG. This company specializes in Silicon thin-film technology. Sources at REC explain that the challenge of new technological solutions is something that must be incorporated into business strategy. This also is a reason for why investment into Silicon production is something not done over night. The plants that were bought in the U.S produce Silane gas which is further produced into so called solar grade silicon by solidifying the gas at high temperatures. A point of strategic importance is that this gas also can be used in the production of thin film solar cells. Thereby REC has secured a raw material capacity that also can be used in case of technological change, and change of dominating design.

- ***Elkem Solar:***

In later years the PV-industry has grown to such an extent that large scale production of feedstock becomes increasingly viable. This has become a point were Elkem has re-entered the industry actively, with the establishment of the company Elkem Solar. As an organizational unit Elkem Solar started up in 2001. This is a continuum and extension of previous efforts of Elkem[32]. At the same time the aspirations have been more focused due to this organizational change. The Elkem management also has seen the business opportunities in these markets and thereby also backed and supported these developments more strongly. One reason for why this is happening at this point in time is the rising size of the solar cell industry. The PV-industry has become a customer worth mentioning in the silicon market only the last 5 years. Furthermore a dedicated production of Solar grade Silicon is only economic in large scale production (Goetzberger et al 2003: 15). This has also been a key factor for establishing the production of dedicated feedstock at this point in time.[33] During the 80ies, when developments were started, the solar cell industry was nonexistent as a customer group. When addressing why these developments have been possible for the company the first point is that Elkem has been involved with Silicon production[34]. The knowledge of making different qualities (Silgrain etc) of Silicon is mentioned as an advantage. All this is based on a long range of innovations bringing Ferro alignment technology into Silicon production. This was possible due to pioneering activities, at the same time as the environment in Kristiansand has been of high importance throughout the years.

The company specializes in the production of Solar Grade Silicon. A testing station in Kristiansand Norway has been used, and the goal of large scale production seems to be viable within in short time. If existing plans are pursued production should start 2007-2008. The establishment of this production facility is of importance for several reasons. First of all this leads to a higher contribution of Silicon to be used in the sector, although there is little concern at Elkem that the competition between Elkem and REC will lead to neither market saturation nor a break-down. Erik Løkke-Øwre at Elkem has stated that the market has room

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[32] Elkem Solar Interview
[33] Elkem Solar Interview
[34] Elkem Solar Interview

for both because of the size of the market.[35] Whether or not this will decrease Silicon prices is yet left to see. Informants at Elkem Solar state that they will enter an existing market, and promote their product related to market pricing levels. With a long history of Silicon production, Elkem now pursues new ways of producing natural resources. Elkem Solar has entered negotiations with business partners concerning sales of Silicon before actual production has taken place.

The production processes pursued by Elkem differ from the ones used by REC, in that they are based on metallurgical processes (Peter Et al. 2005: 1). These processes are new, and differ from the ones used in existing plants by Elkem. Since they are on the verge of establishing production not too much is known about these processes. The important point is nevertheless that they differ from the ones employed by others, increasing technological heterogeneity within the industry.

- ***Norwegian Silicon Refinery:***

As the industry matures and is embedded increasingly within the NIS the number of related organizations increases. The increasing embeddedness of the industry also increases the viability of Silicon production, and the view of this production as interesting. In addition to REC and Elkem producing feedstock for the PV-industry other companies globally seek to be partakers of this growing industry. [36] The same takes place nationally. Norwegian Silicon Refinery (NSR) is a research company that has found a new and cost effective way of producing Silicon for the PV-industry. At the same time they are experiencing problems with market entry and the commercialisation of their product, due to lack of funding and

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[35] http://www.fvn.no/na24/article388342.ece

[36] Recently also two German companies Degussa AG & Solarworld AG announced a joint venture seeking to produce Solar Grade Silicon in a new cost effective process. http://www.solarserver.de/news/news-5523.html

investments. NSR has done research on this since the mid 1990ies. The company has successfully been able to implement a process that has large potential of producing Solar grade Silicon. The process employed by NSR differs from the two aforementioned in that it employs electrolysis processes[37]. Sources at NSR state that this production process is competitive with the ones employed by the production facilities owned by REC today, as well as the production processes developed by Elkem Solar. Nevertheless this company has until now not been successful in implementing this production process in large scale. This has to do with lack of funding for developing a pilot plant for testing of high scale production. NSR views the establishment of a pilot plant as an unavoidable step of the process of production up scaling. This is due to that some parts of the specially developed process like acid baths must be adjusted for large scale production. Nevertheless it seems as if investments at this point in a process are difficult to encourage within the Norwegian national system of innovation. Public funding does not apply at such an amount at this a point in the development process. At the same time private investors have been hesitant largely because of the risks of developing a pilot-plant, and because of little willingness of public funding arrangements. Nevertheless NSR keeps up the work with finding suitable and willing investors for financing such a pilot plant. NSR views RECs Silicon production as a competitor, but keeps faith in that their own process is able to deliver high-grade silicon for wafers at a cost-effective level and has the potential competitive advantage in producing Silicon at lower price levels.

4.4.2 Systemic Interaction and Institutional Setup:

Due to the interactions amongst the NIS and SIS described previously, changes in the institutional setup have grown forth. As discussed previously an institutional setup related to

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[37] Norwegian Silicon Refinery Interview.

Silicon has existed for long periods of time, involving mainly Elkem and central Norwegian research facilities such as NTH / NTNU, but with the establishment of the PV-industry a new institutional context of has arisen. Lundvall (1992) refers to institutions as “rules of the game”. Moreover the concept points towards what governs the interactions between organizations within an innovation system. In this case I apply the concept to describe interactions amongst firms and research agencies, and emphasize that policy aspects regulate some of these institutions.

In the momentum phase the industry has matured, and institutional changes become increasingly embedded in the NIS. A sign of this is the further collaboration amongst firms and research organizations, but in a more structured manner. IFE, NTNU and SINTEF all have contributed with research in the technology development processes of all the firms within the industry. In 2006 a new research centre concentrating on Silicon for the PV industry is established in cooperation between NTNU and SINTEF[38]. IFE is also included into the establishment with the goal of coordinating the research on a national basis. The establishment points towards a further focus within the Norwegian industry on upstream products, with a particular focus on the Silicon bottleneck. At the same time this is not only interesting for the industry in itself, but also shows that this industry is becoming more embedded into existing structures of the NIS, which shows that not only technological change takes place but also institutional. An important factor were the institutional setup, in the form of policies, has been neglecting the industry is in the field of competence building. The importance of competence building within the SI approach has been highlighted in recent years (Edquist 2005, Lundvall 2002). The existing research networks exist of highly skilled scholars. Nevertheless the industry is starting to see a lack of skilled and competent

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[38] http://www.forskning.no/Artikler/2006/september/1158150797.78

workforce, especially with scientific and technical knowledge backgrounds.[39] The debate regarding the lack of technical workforce in Norway is illustrative in this respect[40]. Nevertheless, and due to institutional change, a central task of the newly established research centre is to provide the industry with skilled workforce, and can be seen as a starting attempt of strengthening the institutional setup, and thereby contribute to further growth of the industry.

In addition to these more established research networks more subtle but equally important institutions exist within industry networks. While never completely abandoning the SE industry Elkem has made efforts to be back in the game. Not only do the clear cut aspirations of Elkem Solar point towards a more focused interest to enter the industry, but also the increased shareholding in existing companies within the industry. Elkem has through its parent company Orkla[41] became an important shareholder of REC, which gives them influence on the company. Presently the company seeks to increase shareholding to gain higher control.[42] Ole Enger, group managing director of special materials at Orkla is also board member of REC. These links between the organizations within the sector gives rise to the assumption of an institutional set-up of a tight and close character.

4.5 From Unstructured to Structured:

This chapter has shown that the entry of new technologies, learning processes and knowledge bases increase heterogeneity within the national system. It shows that new industrial paths are

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[39] Elkem Solar interview

[40] http://www.tu.no/nyheter/arbeidsliv/article55631.ece

[41] Elkem is a subsidiary of the Orkla Group. Ole Enger was until 2006 CEO of Elkem, and now holds position as director of special materials in Orkla.

[42] http://www.dn.no/forsiden/borsMarked/article882583.ece?WT.mc_id=dn_nyhetsbrev

created where existing knowledge and technologies are supplemented by external factors. This has taken place due to interactions between the national and the sectoral systems of innovation. In this establishment a key element has been knowledge embedded not only in the SIS, but also in paths and trajectories within the NIS. As has been shown this interaction can take place in differing settings, but that transfer of knowledge and technology is central. In this process the industry has gone from unstructured to structured in that technology and institutions have become increasingly embedded in the national system.

Chapter 5

5 Path Dependency, Policy and Further Developments:

What can we learn from the above mentioned regarding path dependency? I argue that important knowledge foundations in the PV-industry originate in technological trajectories seen within the Norwegian national innovation system, such as the process industry and particularly Silicon production. As mentioned in the technological chapter, small incremental steps that lead to further increases in cost-efficiency are of importance for a further development of technology. The learning processes related to such developments are partly influenced by these technological trajectories, and the dynamics of Silicon production play a significant role. When analysing the links between earlier modes of production (various Silicon qualities) and new processes (SoG) an important similarity is seen in the way small improvements and heterogeneity are drivers of development. I argue that the technological trajectory related to the metallurgical process industry has played an important role in the development of the industry. What was learned throughout the years of Silicon production, particularly with working towards the goal of refining Silicon to higher levels of purity, is determining how and what it produced in the future.

5.1 Path Dependency and Silicon as Dominating Design:

When seeking to explain the importance of Silicon as raw material for the PV-industry, an important issue is to look at the why it is exactly this material that is used. Technically speaking Silicon is not the most effective and suitable material for usage in photovoltaic technology. In fact it is argued that the dominant role of Silicon is quite surprising (Goetzberger et al. 2003: 5). While being rather close to maximal levels of photovoltaic conversion, solid state physics states that this is not the *optimal* material (Goetzberger 2000: 2). Gallium Arsenide is by some referred to as a challenging material for both the microelectronic and the photovoltaic industry. Technically speaking some important properties of this material are more efficient absorption of sunlight, it can operate at higher temperature, and it moves electrons faster than Silicon (Bylinsky 1988: 194). The main reason that Silicon nevertheless is the material of choice in 90% of the technologies, is the knowledge related to the usage and production of this material (Goetzberger et al 2003: 5). As mentioned; Silicon technology has been highly developed before the usage in photovoltaic devices, especially in the semiconductor and microelectronics industry. Regarding the material choice the explanatory factor for choice of material within the Norwegian industry is path dependency. The empirical evidence points towards the importance of embedded knowledge related to the production and usage of Silicon as raw-material. Given the long history within Silicon production the existing knowledge of Silicon is seen as a natural determinant in the choice of material. Therefore I argue that the existing trajectory within this technology can be seen as leading further developments. Hence, although Silicon is not the optimal material, although it is well-suited for use in photovoltaic technology, the knowledge related to this specific material is of crucial importance with respect to the developments of the sector. Given the above mentioned path dependency related to choice of material is viewed as an explanatory factor. Furthermore this can explain the focus of the Norwegian industry on upstream products. The embedded knowledge to industrialization of processes determines the mode of production, and the focus on Silicon production.

According to Andersson &Jacobsson (2000) technical change has a way of changing factors in production processes. Depending on the maturity of the design and technology it is stated that when a dominating design has been reached this also changes the dynamics of both firms and others (Andersson &Jacobsson 2000: 1039). A key dynamic factor is the change in R&D allocation, from product to process development. The Norwegian industry entered the sector at a point where a dominating design was Silicon based PV-technology, and has contributed with central process developments in Silicon production. As mentioned previously, 90% of the PV production is based upon Silicon as raw material, making Silicon based crystalline PV-technology the dominating technological design. Nevertheless the challenges of thin-film technologies now seem evident. These challenges are first of all seen in the technological capabilities, in that efficiency of the thin-film technology has the possibility to exceed the one of traditional silica-based PV technology. Furthermore the production processes of such technology avoid the steps of crystallization and wafer sawing (Goetzberger 2003: 1). Predictions in further decreases in production costs for thin-film technology also seem challenging. Nevertheless Silicon based crystalline PV technology has high growth rates, and has been dominating the last decades. With an increased Silicon production capability the dominating role of crystalline Silicon based designs may also uphold.

5.2 Path Dependency and Systemic Lock-in:

When discussing path dependency a central related issue is the topic of systemic lock-in. Narula (2002) argues that a systemic lock-in characterises the Norwegian national system of innovation. The process industry has been a central element of the national system of innovation for decades, and is an area where Norway has a strong position. The negative systemic lock-in particularly concerns the NTNU / SINTEF environment and its relation to the process industry. Moreover the argument is that inertia in R&D location has a close relation to structural inertia. A negative systemic lock-in is a result of this inertia. National R&D structures like NTH, and later NTNU / SINTEF, have had dominating role related to the process industry. Furthermore it is argued they have been dominated of internal and informal networks, making the structures less open to external influence due to negative systemic lock-in.

What the case in this paper shows is the contrary. The Norwegian industry, and moreover the national system of innovation, has in this case proven to be open to external influence through influence of the sectoral innovation system. This goes for firms as well as the research environment. R&D structures have also adapted themselves to institutional and technological change with external influence of the sectoral system. In this case this displays adaptability and openness of the national system.

5.3 Policy Implications- Path Dependency and the Norwegian Photovoltaic Industry:

What can be learned regarding policy from the material presented? Regarding the establishment there is no obvious reason based on the technological artefact itself that explains the establishment of photovoltaic technology in Norway. Even though several issues, like a certain will to focus on renewable energy[43] and the recent debate regarding an energy crisis[44] has brought energy questions more clearly into the public debate, photovoltaic energy is not regarded a viable energy producer in Norway due to geographical reasons. There is therefore no evident reason, other than that the knowledge embedded within national structures that can explain the establishment of this industry in Norway. In extension the interaction with external sources also is decisive. The assumptions give rise to central implications for policy. First, the knowledge embedded within national structures has been decisive in the establishment of the industry. Furthermore the material presented has shown a traditional industry adapting to technological change and being highly innovative. Policy should therefore reflect that knowledge embedded within traditional industries, such as the process industry, has the potential of contributing to innovation and growth. Second; the ability to adapt to technological change to a large extent has depended on interactions between the national and the sectoral systems of innovation. This shows the importance of industrial networks and institutions that facilitate knowledge and technology transfer. A second policy implication should therefore be the importance of facilitating industrial networks that can further enhance the absorptive capacity of the industry related to external influence.

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[43] RENERGI; Norwegian Research Council Program that focuses on renewable energy

[44] http://www.tu.no/energi/article58013.ece

Furthermore, the view of the process industry as fading away in the context of globalization, with relocation of production facilities to cheaper locations, is rather deterministic. The knowledge embedded within traditional structures should be viewed as a resource, with potential of contributing to new modes of production and heterogeneity within the national system of innovation. Thus innovation and economic growth can be seen as resulting out of new combinations of existing structures, where the traditional and national characteristics play a central role.

Chapter 6

6 Summary and conclusions:

The paper has asked why and how the photovoltaic industry has been established in Norway, and moreover why this industry is based on producing upstream products. In addressing these research questions the paper has described and analysed PV-technology both on a general and specific basis. In doing this the paper has opened up the black-box of technology, and shown that what is seen as a single innovation (PV-technology) in fact consists on a set of innovative activities on a set of different technological levels. In combination this set of innovations contributes to a further growth of the industry, and diffusion of the technology.

The paper has described the establishment and growth of the industry in Norway from traditional Silicon production to wafer production to production of specialized Silicon feedstock. As shown; the industry and its related innovation processes in Norway are first of all characterized by continuity but also by rupture. The continuity is important to point out because the industry has grown forth within a systemic context where path dependency issues have been determining. Moreover path dependency issues have coloured the mode of production and given it a characteristic national flavour, which has made the industry highly competitive within a global growing sector. The upstream focus of the industry is therefore explained by path dependency issues, where embedded knowledge structures within the national system of innovation have been particularly central. When answering why the industry has been established in Norway these issues are also seen as explanatory.

Furthermore the process as a whole cannot be seen as a linear movement, but rather as process where rupture is characteristic. Technological and institutional change through the establishment of the PV-industry contributes to heterogeneity within the national system. In describing how these developments have taken place a central issue has been to show how the variety of knowledge and learning processes originating within two interacting innovation systems; the national and the sectoral, has contributed to the establishment and growth of the Norwegian PV-industry. Therefore the systemic interaction is seen as an explanatory factor for the establishment of the PV-industry in Norway.

In order to become increasingly successful, both in relation to further industry growth and technological diffusion, the central issues of cost reduction of processes have been identified. A focal area for the Norwegian PV-industry regarding cost efficiency has been related to the main bottleneck of dedicated Silicon feedstock production. The paper has analysed how companies have been focused on, and have addressed this bottleneck differently, showing that this is a level of production with great potential both related to growth, but also regarding increased total PV-production.

The paper has argued that a diffusion of PV-technology has a background in the viability and cost of the technology. This viability is readily increased, at the same time as companies seek to apply increasingly cost-efficient processes in production. When looking at the developments holistically, or as a collective effort, key elements are the movement towards higher viability, lower prices and increased diffusion of the technology. These efforts are seen as partaking in the prolonged and unfinished innovation processes leading to an increased diffusion of photovoltaic technology.

The diffusion of this technology is important for a further growth of the PV-industry, and on a higher level, also for growth of the share of total energy production based on renewable solar energy. Such a growth is possible through further technological change. Whether or not such growth will be based on the dominating design of traditional PV-technology, which this paper is based on, or challenging technologies is left to see. In either case, Silicon based designs are dominating at this point in time and are believed to be central in the years to come. This gives the Norwegian industry the advantage of an early presence within this specialized industry. The further development of the industry and its contribution to cleaner energy production relies on companies to further decrease production prices.

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