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Potential areas of success for Northern European firms in the PV industry

Supported by a historical perspective

Master of Science Thesis in the Industrial Ecology and Management and Economics of Innovation Programmes

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Göteborg, Sweden 2014
Report No. 2014:16

MASTER'S THESIS 2014:16

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Chalmers Reproservice
Göteborg, Sweden 2014

Abstract

The past decade, the photovoltaic (PV) industry has grown from small and regional to global. This development is important to understand. It can explain what has driven growth and indicate where the industry is heading. Doing so also enables the identification of parts of the PV industry where Northern European firms could compete. The study is a qualitative case study that has been conducted with an inductive approach. Data was gathered through document readings and through interviews with people knowledgeable of the industry.

The German feed-in tariff introduced in 2004 gave the European PV market a push forward. Demand exceeded supply and firms entered the industry. The increasing demand led to a global polysilicon shortage in the mid 2000's. Meanwhile, newly established Chinese firms increased their capacity significantly and module prices declined. Combined with reduced subsidies and the financial crisis, this led to an industry consolidation. While the European market stagnated, the Chinese market was boosted by domestic policies and became the world's largest in 2013. The consolidation also brought protectionism. The US and EU imposed duties on Chinese cells and modules, and China followed by imposing duties on imported polysilicon.

Currently, the industry is characterized by overcapacity, although not as severely as a few years ago. The consolidation has slowed down and the industry shows signs of recovery. The market grows largely due to high installation rates in Asia, mainly China and Japan. China is by far the dominating manufacturing nation in the PV value chain, even if other countries still have production in certain technologies or parts of the value chain. Main applications vary substantially between markets, much due to local policy instruments.

Scale benefits, low costs, and a large domestic market expect to maintain the Chinese dominance. Firms in Northern Europe are more likely to succeed in R&D, development and manufacturing of equipment, or in the downstream value chain. Which is most suitable depends on each nation's firms and competences.

Key concepts: PV industry, industry development, value chain development, locational advantages

Acknowledgments

We would like to seize this opportunity and express a big thank you to those who have helped us to conduct this master´s thesis. Special thanks go to our tutor Björn Sandén for feedback and supervision, and to all interviewees for sharing their time and knowledge with us.

Julia and Eleonor
Gothenburg, August 2014

Preface

This master thesis is a part of the project 'Technological innovation systems in the energy sector' commissioned by the Swedish Energy Agency. The overall aim of this project is to gain an understanding of how political efforts can contribute to industrial development in the Swedish energy sector.

Glossary

Efficiency	Measure of how much of the sunlight a solar cell converts into electricity
EU15	Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the United Kingdom
Feed-in tariff	Policy mechanism imposing utilities to pay PV system owners a fee for the electricity they feed into the electricity grid
Photovoltaic (PV)	‘Photo’ stands for light and voltaic for the generation of voltage (and current)
PV industry	Used in reference to the ’solar cell and module industry’
Technology specific policy	Governmental policy targeted at a particular technology
Turn-key manufacturing line	Production line sold to a producer ready to use without further installations or add-ons

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1. Introduction

This chapter will provide a background to the master thesis with the intention to motivate the importance of the chosen subject and to introduce the topic to the reader. The purpose will be presented and broken down into research questions and the scope of the thesis will be discussed.

1.1 Background

The global demand for energy is increasing, particularly in developing countries. If the development continues in its current direction and pace, the global energy demand will have increased with 65 per cent between 2004 and 2030. Reducing carbon emissions while satisfying the increasing energy demand will require a major energy transition. The majority of the world's energy consumption is still, however, concentrated to the western world. In these areas, the energy demand is rather stable and the challenge lies in replacing traditional non-renewable energy sources with renewable. Solar cell technology is likely to become an important technology in this energy transition (IPCC, 2007).

The potential of solar energy is large compared to that of many other energy sources (Maugeri, 2010). The solar energy reaching the earth's surface every year covers around 10 000 times the world's annual energy consumption (IPCC, 2007). Solar cells, or more specifically photovoltaic (PV) cells, directly convert sunlight to electricity. PV cells are grouped into modules, in which the cells are electrically connected and packaged into frames (Thorpe, 2011). The energy produced by PV modules does not only rely on a renewable source of energy, it is also safe, reliable, and pollution free (Zhao et al, 2013).

The PV industry has grown rapidly the past decade and it has gone from a small localized industry centred in Germany to a global-reaching industry that is now on governments' agendas all over the world (Aanesen, Heck, and Pinner, 2012). A main driver of the rapid development of the PV industry has been, and still is, governmental initiatives. Europe has been the leading region in installed PV capacity, with about 70 per cent of total global capacity in 2012. Recent developments have resulted in that other markets than Europe, mainly China, the US and Japan, now drive industry growth. The global accumulated PV capacity added up to 24 gigawatts in 2009 and reached over 100 gigawatts in 2012 (see Figure 1.1). This amounts to the energy needed to supply 30 million European households with electricity during one year. Despite the past years' impressive growth rate, the share of the world's electricity demand supplied by PV is still less than 0,5 per cent, and there is still large growth potential left for the PV industry (EPIA, 2014a).

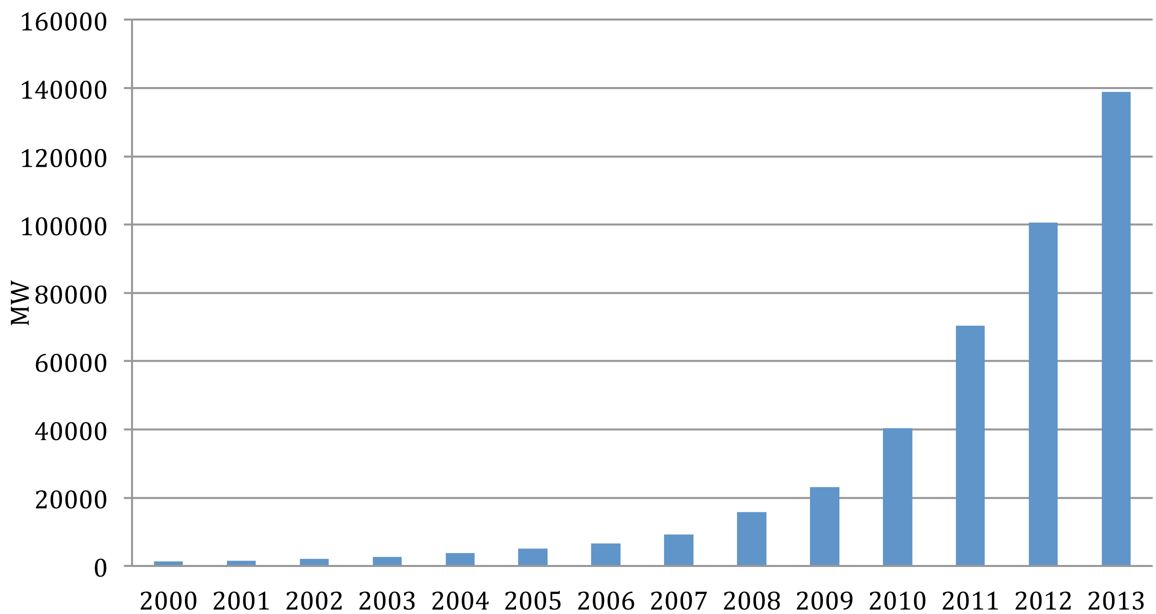

Figure 1.1: The world´s cumulated installed PV capacity, 2000-2013. Source: EPIA (2014a)

During the past decades of growth, firms have entered and exited the PV industry, and the geographical location of firms and their manufacturing facilities has shifted from predominantly Europe, Japan, and the US to Asia - China in particular (EPIA, 2014a). There is still interest from firms in Northern European countries to possibly enter the PV industry. It is not clear, however, in which parts of the PV industry it is likely that these firms would be able to compete. Distinguishing historical patterns and trends of the PV industry and its value chain can assist in identifying such opportunities. This will enhance the understanding of which factors that has enabled growth, indicate in which direction the industry is going, and which type of actors and nations that are likely to dominate the industry in the upcoming years.

1.2 Purpose

The purpose of the thesis is to identify parts of the PV industry where firms in Northern Europe possibly could become internationally competitive.

1.3 Research questions

Research questions support the research process in several ways. For instance, they can guide the literature study and the data collection, as well as making sure the research stays within the boundaries of the research topic (Bryman and Bell, 2003). To fulfil the purpose of the study, the three research questions presented below need to be answered.

RQ1 How has the PV industry developed during the past 15 years?

RQ2 What characterises the PV industry of today?

RQ3 In which parts of the PV industry is it likely that firms from Northern Europe can compete successfully?

An industry is constantly changing, and a historical perspective enables insights in historical patterns and enhances the understanding of the current state and trends of the industry. Therefore, answering RQ1 provides an understanding of the industry as well as supports the investigation and analysis related to RQ2 and RQ3. The current state of the industry is the starting point for any future development, and RQ2 is hence crucial to answer. RQ3 clearly aims to answer the main purpose regarding the possible future role of Northern Europe.

1.4 Scope

The description of the PV industry and its development is limited to key industry events and the geographical locations where these have taken place. Further, the historical description of the industry and its value chain development does not go back to when the technology was first developed. Instead, it begins in the early 2000's when the technology gained momentum and experienced large growth in relation to previous levels.

Within the PV industry, there is a wide range of competing technologies. To map the value chain for each one of these would be time consuming and not necessarily relevant. The report therefore focuses on the value chains of the most widely used PV technologies, mainly the crystalline silicon and thin film technologies. The unit of analysis is the PV cell and the PV module. A PV system, however, requires other components such as inverters and sometimes storage solutions. These components do not lie within the scope of the thesis. Finally, governmental policies and incentive programs have largely driven the growth of the PV market and industry. Such policies and incentive programs are brought forward as key events and drivers, but an extensive analysis of the effects and outcomes are not included.

2. Theoretical framework

The chapter introduces the theoretical frameworks that will be used to answer the research questions. First, the industry life cycle and the technology life cycle models are presented. This is followed by a section about division of labour and the vertical scope of firms. Finally, research connected to what makes countries competitive is brought forward.

2.1 Industry life cycle

Even though industries are different from each other and have different characteristics, most industries have a similar evolution pattern. Figure 2.1 illustrates the industry life cycle model, which describes how industries evolve and divides the lifetime of an industry into four stages; introduction, growth, maturity, and decline. The length of the industry life cycle differs between industries. Moreover, it is uncommon for an industry to be in the same life cycle stage in all countries (Grant, 2010).

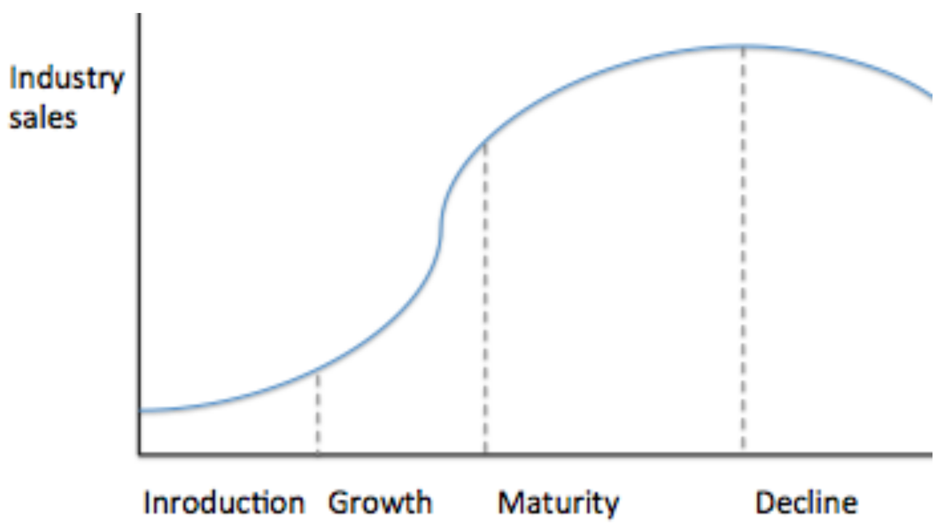

Figure 2.1: The industry life cycle model

Typically, sales are small in the introduction stage and small-scale production combined with little or no experience often results in high costs and low quality products. In this early stage of an industry, firms tend to compete with technology and design. Hence, there are often several competing technologies available on the market and a key to success lies in product innovation (Grant, 2010). The many changes in product design require general-purpose production equipment (Anderson, 1988). Moreover, the production requires high-skilled labour, and therefore tends to be located in advanced industrialized countries. As prices often are high, the markets for new industries are usually also found in such nations (Grant, 2010).

In the growth stage, as the quality of the product increases and the price decreases, the industry's sales accelerate. The growth stage is characterized by rapid process innovation and firms scale up towards mass production in order to meet the increasing demand. The demand from international markets is generally covered by exports from advanced industrialized nations. It is not uncommon that demand exceeds supply, making the industry profitable and hence attractive to new entrants (Grant, 2010). The number of firms in an industry often increases substantially during the growth stage, and the entry rate usually peaks at this point in an industry's lifetime. An industry with many entrants often has high innovation rates and increasing efficiency of manufacturing (Geroski, 1995), which are two other characteristics of the growth stage (Grant, 2010).

As the market reaches saturation, most of the demand will be driven by replacement purchases and the industry enters the maturity stage. Firms that increased their capacity during the growth phase can now gain advantages connected to economies of scale. Combined with a saturated market, this can result in overcapacity where price becomes a key competitive factor (Grant, 2010). Price competition is a common characteristic of a mature industry (Theyel, Taylor, and Heffernan, 2011). With tough price competition, many industries enter what is known as a 'shake-out', during which firms' failures increase sharply (Grant, 2010). This is a turbulent time with bankruptcies, mergers, and acquisitions (Theyel, Taylor, and Heffernan, 2011). After a shake-out, there tend to be few firms entering and exiting the industry, and the firms that are left have reasonably good odds of surviving. Other common developments during the maturity stage are that the product becomes more of a commodity and that the production requires less advanced labour. Production can then move to newly industrialized nations and eventually to developing countries with low labour costs, leaving the advanced industrialized nations as importers (Grant, 2010).

Finally, during the decline stage, the market shrinks as the industry is challenged by substituting products from new industries. This results in chronic overcapacity and the industry is likely to see further price competition as the remaining firms battle for market share. The product is now a commodity, which is both difficult and expensive to differentiate, and hence there is little or no product innovation at this stage. Most commonly, the entire demand is supplied with exports from the nations with the lowest labour costs (Grant, 2010).

2.2 Technology life cycle

In technology intensive industries it is common to talk not only about an industry life cycle, but also about a technology life cycle. The model was first developed by James Utterback and William Abernathy in the 1970's and describes how the rate of product and process innovation changes over time for a technology. Figure 2.2 illustrates the technology life cycle model and shows the three phases a technology passes through; the fluid phase, the transitional phase, and the specific phase (Taylor and Taylor, 2012).

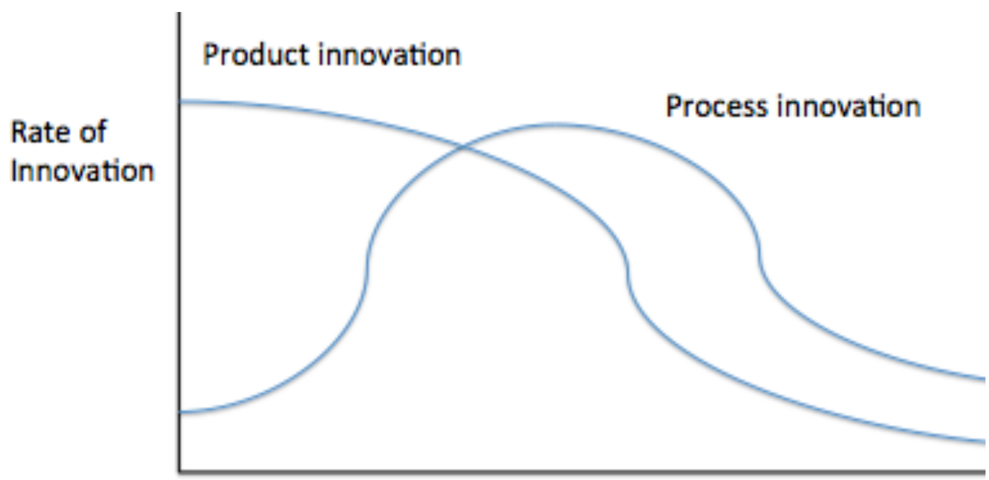

Figure 2.2: The technology life cycle model

The fluid phase is dominated by product innovation and takes place in the early stages of technology development. This phase is sometimes referred to as an 'era of ferment', encompassing several competing technologies simultaneously (Taylor and Taylor, 2012). The fluid phase of the technology life cycle is closely connected to the introduction stage of the industry life cycle, which is also characterized by a high degree of product innovation and where a dominant product technology is yet to emerge (Grant, 2010).

The transitional phase begins with the emergence of a dominant design. A dominant design is one that can achieve production of significant volumes (Anderson 1998) and that sets a standard of looks, functions, and production that is accepted by the industry as a whole (Grant, 2010). A dominant design is not necessarily the technologically superior alternative, but it tends to become the lowest-cost option due to high volumes (Anderson, 1988). According to Anderson (1988), a design needs to capture 50 per cent of the market before it becomes dominant.

The dominant design affects an industry in several ways. First, product innovations shift from radical to incremental which reduces risks for both market and industry (Grant, 2010). Second, the level of product and process innovations becomes more balanced as larger focus is placed on process development in order to enable large-scale production (Taylor and Taylor, 2012). As uncertainty decreases with the higher degree of standardisation, firms are willing to invest in larger manufacturing facilities and produce higher volumes (Anderson, 1988; Grant, 2010; Geroski, 1995). The competition shifts from being based on product design to focus more on prices and cost efficiencies. This shift creates entry barriers for new entrants in the form of economies of scale and decreasing possibilities for product differentiation (Geroski, 1995).

The early stages of the transitional phase have similarities with the growth stage of the industry life cycle, which is characterized by process innovation and firms scaling up production (Grant, 2010). As the transitional phase progresses, it has more in common with the maturity stage. Price competition intensifies, ultimately resulting in a firm 'shake-out' where less efficient firms and firms that chose a technology that did not become dominant disappear (Peltoniemi, 2011). Another common effect of a dominant design is the commoditization of the product, which also is evident in the mature stage of the industry life cycle (Grant, 2010).

Eventually, the technology life cycle reaches the specific phase. In this phase, changes in product or production process tend to be expensive, which is why the general level of innovation is low (Taylor and Taylor, 2012). This is similar to the situation in the decline stage of the industry life cycle (Grant, 2010). The emphasis lies increasingly on cost efficiencies, incremental improvements, and large-scale capital-intensive production facilities (Anderson, 1988).

2.3 The vertical scope of firms

The degree of vertical integration regards the degree to which a firm performs different activities within the firm. A firm that performs many steps of a value chain is vertically integrated, whereas a firm who specializes on a single part of the value chain is not. Main advantages connected to vertical integration include greater coordination and less risk, whereas commonly mentioned disadvantages are reduced flexibility and less focus on core competencies (Grant, 2010).

2.3.1 Division of labour

If two people have different skills, it is more effective for both to specialise in what he or she does best and trade outputs with each other. This is the basis for division of labour, which essentially means that it is inefficient for everyone to produce everything they need themselves (Beinhocker, 2006). Division of labour is another term for specialization and it is central for increased productivity (Beinhocker, 2006; Swann, 2009). For division of labour to make sense economically, the market needs to be large enough to justify specialization. On global markets, companies tend to specialize on a small part of the value chain to gain advantages connected to economies of scale (Swann, 2009).

Division of labour also requires coordination of tasks and cooperation between actors. This challenge increases with higher degrees of division of labour and creates a trade-off between specialization and coordination (Grant, 2010). Grant (2010) argues that if the external environment is stable, the costs of coordination decrease. Therefore, a higher degree of division of labour is justified in industries with a stable external environment.

2.3.2 Transaction cost economics

Transaction cost economics seeks to explain why firms in some cases specialize and why they sometimes vertically integrate (Grant, 2010; Swann, 2009). Ronald Coase concluded that firms will choose to vertically integrate or not, depending on which option that minimizes transaction costs (Beinhocker, 2006). Transaction costs are the costs related to using the market and represent any costs besides the price for the product itself. Examples of transaction costs are search costs, costs of communicating with other firms, and costs of writing a contract (Grant, 2010; Swann, 2009). Conditions external to individual firms affect transaction costs. For instance, the emergence of standards and a dominant design can reduce transaction costs and hence lead to an increase of division of labour (Swann, 2009).

2.3.3 Conditions appropriate for vertical integration

Whether vertical integration is good or bad for a firm depends on several things. It depends on the size of the market (Swann, 2009), on how stable the external environment is (Grant, 2010), and on the amount of transaction costs (Beinhocker, 2006; Grant, 2010). Jacobides and Winter (2005) argue that to understand why firms choose to vertically integrate, transaction costs need to be analysed together with firms' capabilities. For division of labour to occur, firms cannot all have the same capabilities because then all firms would specialize on the same part of the value chain. Hence, low transaction costs can only lead to a high degree of division of labour when firms have heterogeneous capabilities (Jacobides and Winter, 2005). Firms who do specialize can develop their capabilities in their respective areas and firms' capabilities can through this path dependent process become increasingly heterogeneous (Grant, 2010). Therefore, when firms change their vertical scope, they also change their future capability development (Jacobides and Winter, 2005).

According to Wise and Baumgartner (1999), manufacturers tend to be in a good position to perform downstream activities such as financing or maintenance, because they are knowledgeable about their products and the markets these are sold on. A downstream move is however not profitable for all manufacturers. Sometimes, a downstream move is not as much of a choice as a necessity, for instance when the possibilities to differentiate the product is declining (Wise and Baumgartner, 1999).

Grant (2010) lists further factors to consider while deciding whether or not to vertically integrate. Different steps of a value chain may require different scales of production, which may or may not be compatible. Moreover, even if two businesses are vertically related, they can be very different strategically. One step of the value chain may for instance involve business-to-business sales, while another vertically related step uses business-to-customer sales. These two steps of the value chain may be beneficial to integrate production wise, but they need very different marketing strategies. Grant (2010) points out that such strategic differences have had a large impact on the trend towards a higher degree of division of labour. Other factors to take into account are the need for flexibility and the competitive effects related to becoming a competitor of your customers (Grant, 2010).

2.4 Competitiveness of countries

Many industries' production is increasingly concentrated in China. Previously leading production nations, specifically the US and many European countries, have seen their competitiveness decrease. Competitiveness on a country level depends on factors such as productivity and nation-wide policies. Essentially, it comes down to the ability to produce, sell, and supply goods and services good enough to meet international demand and competition (Zhang, Ebbers, and Mulder, 2012).

The factors that determine where firms choose to locate production facilities differ among industries and product ranges (Blair and Premus, 1987). The classical factors that affect locational decisions include transportation costs, labour costs, and market size (Blair and Premus, 1987; Wheeler and Mody, 1992). Blair and Premus (1987) highlight the importance of infrastructure development, stable international affairs, and a domestic market that is increasing in size. Porter (1990) includes all of these and more to explain national advantages in certain industries. According to Porter (1990), factor conditions such as skilled labour and infrastructure, and demand conditions where the domestic market is in the centre, highly affect a nation's competitiveness. He also, however, include related and supporting industries, meaning that a skilled supplier base can be of high importance, and firm strategy, structure, and rivalry in which organisational structures play an important role. Together, these four attributes determine competitiveness in a given industry

(Porter, 1990). Once a locational advantage has been achieved, it tends to strengthen itself as more development efforts are made and more firms establish (Wheeler and Mody, 1992).

On a country level, size and specialization correlate. Large countries are often diversified in terms of economic activities, whereas small countries tend to have more specialized areas of production. The EU15 has the past decades seen industries moving to low-cost/high-tech countries in Asia and Eastern Europe. Siemens and Volkswagen for instance now produce a majority of their products outside of Germany (Stajano, 2009). Zhang, Ebbers, and Mulder (2012) investigated the competitiveness of industries in China and in EU15 by looking at each industry's competitiveness in the different countries. They found that in most industries, China follows the competitiveness pattern of EU15 in the sense that in an industry that is highly competitive and profitable in EU15 tends to be emerging in China. Similarly, an industry that in EU15 is losing competitiveness and is on decline is likely to be highly competitive and profitable in China. The reasons could be many. A fall in productivity in EU15 can for instance give Chinese firms a chance to grow, while an increase in Chinese competitiveness can cause EU15 firms to struggle. Note however that these relationships do not have to be causal. Other countries and factors in the external environment also affect the competitiveness (Zhang, Ebbers, and Mulder, 2012).

3. Methodology

This chapter explains how the study has been conducted and motivates chosen research type, research design, and research methods. The chapter ends with a discussion regarding credibility.

3.1 Research type

To answer the research questions and fulfil the purpose of the study, a thick empirical description of the PV industry was necessary. The study has been performed with an inductive approach, meaning that most of the data collection and parts of the analysis preceded the study of theory (Bryman and Bell, 2003). Theory has been used mainly to structure the empirical chapters and give the reader a context of analysis. Most commonly, an inductive approach results in a largely qualitative study (Bryman and Bell, 2003), which tends to be subjective, descriptive, and inductive (Blaxter, Hughes, and Tight, 2006). A qualitative study method is appropriate if there are open-ended research questions and text-based rather than numerical data (Creswell, 2003). Both these conditions hold true in this study, motivating a qualitative research method. It is possible to use a mixed method where both qualitative and quantitative data is collected and analysed (Creswell and Plano Clark, 2011). This study uses quantitative data to describe the growth and development of the PV industry over time to illustrate and complement the qualitative data. The vast majority of the collected data is however qualitative and it is therefore fair to say the study is of qualitative nature.

3.2 Research design

As the study focuses on describing and analysing the development and current state specifically of the PV industry, a case study design is appropriate. A case study tends to be an extensive description and analysis of what often is a single case (Bryman and Bell, 2003). In a case study, the complexity and interconnectedness of the data can make the analysis difficult (Creswell, 2003). Therefore, it has been important to make appropriate delimitations to gain control of the scope. When the research strategy is qualitative, such as in this study, it is common for a case study to have an inductive approach (Bryman and Bell, 2003). Hence, the combination of an inductive approach, a qualitative research method and a case study design is highly motivated.

3.3 Research methods

Research methods are simply the methods used to collect data, which is either primary or secondary. Primary data is collected to perform the study at hand whereas secondary data has been collected as primary data in another study or for another purpose (Bell, 2006). The main research method for primary data in this study has been interviews, whereas the main research method for secondary data has been document readings. Furthermore, during the annual Intersolar conference in Munich, an international solar exhibition, additional primary data was gathered through personal communication.

3.3.1 Document readings

Document readings has been a vital data collection method throughout the study process. It is often much less time consuming and more cost efficient than interviewing (Blaxter, Hughes, and Tight, 2006). In the very early stage, industry reports from organisations such as the European Photovoltaic Industry Association (EPIA) and the International Energy Agency (IEA) provided an overview of the PV industry's main characteristics and key actors. As the understanding of the industry grew, financial reports and webpages of various firms in the PV industry became a main data source. Even though these sources are not included in the reference list, they have contributed significantly to a general understanding of the industry and the firms that operate in it. The annual reports and webpages that supported this learning process are listed in Appendix I. These gave important insights in, among other things, manufacturing processes, the degree of vertical integration, and key markets and application areas. Throughout the entire study process, books and articles complemented the industry and financial reports with more event-specific data. Company websites have been yet another key data source which have been used during the entire study process.

3.3.2 Interviews

Although much important data was gathered through document readings, there were information gaps that needed to be filled. Specifically, as the document readings covered RQ2 rather well, interviews were necessary to answer mainly RQ1 and RQ3. According to Creswell (2003), interviews are useful when the interviewee has historical information hard to obtain elsewhere (Creswell, 2003). As much of the data on the historical development of the PV industry from the document readings was fragmented and incomplete, completing the description of the historical development was an aim of the interviews.

To identify potential interviewees, two approaches were used. First, a couple of researchers connected to the PV industry were asked to advise who they thought might be able to provide useful insights. Second, the document readings had resulted in a list of firms and organisations interesting to the study. All in all, seventeen interviews were conducted to collect primary data to the study. The interviewees are representatives from firms in all parts of the PV value chain, consultants within the energy sector, researchers, or in another way industry experts. Furthermore, the key technologies have been covered through the different expertise of the interviewees. All interviewees are listed in Appendix II.

Most interviews were conducted in Germany, where much of the PV industry development has taken place. Face-to-face interviews hold many advantages over telephone interviews. They allow the use of non-verbal communication, there are no time delays, it is easier for the researcher to build rapport, and it becomes possible to use visual aids (Bryman and Bell, 2003; Opdenakker, 2006). For these reasons, a majority of the interviews were conducted at the respective interviewee's office in Germany. In those cases a face-to-face interview was not possible, the interview was conducted over telephone. The interviews were all semi-structured with open-ended questions, allowing the interviewee to somewhat interpret the questions and answer freely. The questionnaires were in each case written especially for the interviewee and the firm or organisation the interviewee represented.

3.3.3 Personal communication

Intersolar Europe is the largest exhibition for the solar industry in the world. It takes place in Munich each year and this year, 2014, more than 1100 exhibitors participated (Intersolar Europe, 2014). Even though the name suggests otherwise, Intersolar Europe is a global industry exhibition with firms and organisations from all parts of the world present. As almost all interviews have been conducted in Germany and with German firms or German industry experts, Intersolar Europe provided an opportunity to gain perspectives from other parts of the world where the PV industry has developed. Hence, at Intersolar Europe the aim was to talk to representatives from firms and organisations in other key nations of the PV industry, specifically China, the US, and Japan. As the exhibition took place after most interviews had been conducted, it was possible to identify information gaps in the data, which could specifically be targeted. Beforehand, a few key firms were selected and short questionnaires were prepared for these, as time was expected to run short. The data collected from such conversations during Intersolar Europe is categorised as personal communication. A list of those who provided the data is presented in Appendix II.

3.4 Reliability and validity

To assess the trustworthiness of a research study, it is common to evaluate the study's reliability and validity. Reliability relates to whether another researcher could replicate the study and come up with largely the same results (Bell, 2006). Reliability, however, is mostly relevant for quantitative research, much due to the subjectivity of qualitative research. Each researcher has subjective opinions and biases affecting how the qualitative data is interpreted, and hence the results could differ if another researcher had performed the study (Bryman and Bell, 2003). Due to the qualitative nature of this study, validity is therefore the measure left to ensure the study's trustworthiness.

Validity is the degree to which the conclusions of a study are sufficiently motivated. In qualitative research, evaluating validity is mostly about determining whether the collected data is accurate or not (Creswell and Plano Clark, 2011). To increase the validity of a qualitative study, Creswell (2003) suggests researchers to make use of triangulation, to use thick descriptions, and to clarify any biases of the researchers that may affect the outcome. Each of these three will be discussed below in relation to the study at hand.

3.5.1 Triangulation

Triangulation means that the researcher uses several data sources to obtain basically the same data (Creswell and Plano Clark, 2011). This provides a basis for generalisation and hence external validity (Maxwell, 2005). The data collection described above incorporates mainly document readings and interviews. These methods do not only complement each other but are also used to control the accuracy of the gathered data. Information that has been consistent regardless of interviewee or document type has been considered valid. When the data from different sources at one point contradicted each other, it signalled a need to dig deeper into the issue. Further, the documents have been of various kinds and have been written with different purposes by different authors, and so data derived from different types of documents also validate each other. All in all, the different data collection methods used have successfully strengthened the validity of the gathered data.

3.5.2 Thick case descriptions

A thick description increases face validity, as it gives the impression of a valid set of data to analyse and draw conclusions from. It also increases internal validity as it enables a deeper understanding of the case at hand and provides the researcher with valuable insights (Creswell, 2003). To describe the PV industry and its development demanded a thick description in itself. Data have, as described above, been gathered from multiple sources and the amount of data exceeded the need. As a result, not all information made it into the report. The large amount of data has provided a comprehensive understanding of the industry and its value chain, hence making the analysis and arguments highly motivated.

3.5.3 Biases

Acknowledging the researchers' potential biases increases validity as it shows the researchers' awareness of potential pitfalls (Creswell, 2003). The researchers of this study may have been affected by biases related to their educational background.

However, the awareness of the issue has decreased such biases, even if it is close to impossible to avoid them completely. Moreover, without these educational backgrounds it would have been difficult to understand the industry structure and value chain. Hence, even if the educational background may have narrowed the train of thought at some point, it would not have been possible to conduct the study without it.

Besides from potential biases of the researchers, there are potential biases of interviewees to take into consideration. These biases are often related to the work and research background of each respective interviewee. By interviewing people with different backgrounds and by using triangulation of the answers, the negative effects of potential biases have been reduced.

4. Main PV technologies

In this chapter, the two main PV technologies crystalline silicon and thin film are presented. Their respective advantages and disadvantages are outlined, and the most important aspects of manufacturing are covered. The chapter begins with a basic explanation of how the PV technology works.

A PV cell converts energy from sunlight into direct current through the photovoltaic effect. A PV cell can be made from various semi-conducting materials, and silicon is the most widely used material. PV cells have a structure of two layers or more, each layer having either positive or negative potential. When sunlight hits the semi-conductive material, the photons' energy is absorbed and transmitted to an electron, which is knocked out of its orbit and attracted to the layer with positive potential. The layers of the cell are connected in a circuit, creating an electric current (Thorpe, 2011).

Different PV technologies use different types of semi-conductive materials or compounds. Figure 4.1 shows the efficiency development of the different PV technologies. However, it is important to keep in mind that the record cell efficiency only indicates the potential of each technology. In order for a PV technology to be successful, it has to have sufficient module efficiency and low production costs. At the end of the day, what PV technologies compete on is the cost per watt produced.[1] Not all PV technologies are produced on a large scale. The remaining part of this chapter will describe the most widely used PV technologies: crystalline silicon and thin film.

[1] Stefan Müller, Member of the Board/ Chief Operating Officer, Enerparc, Interviewed May 19th 2014

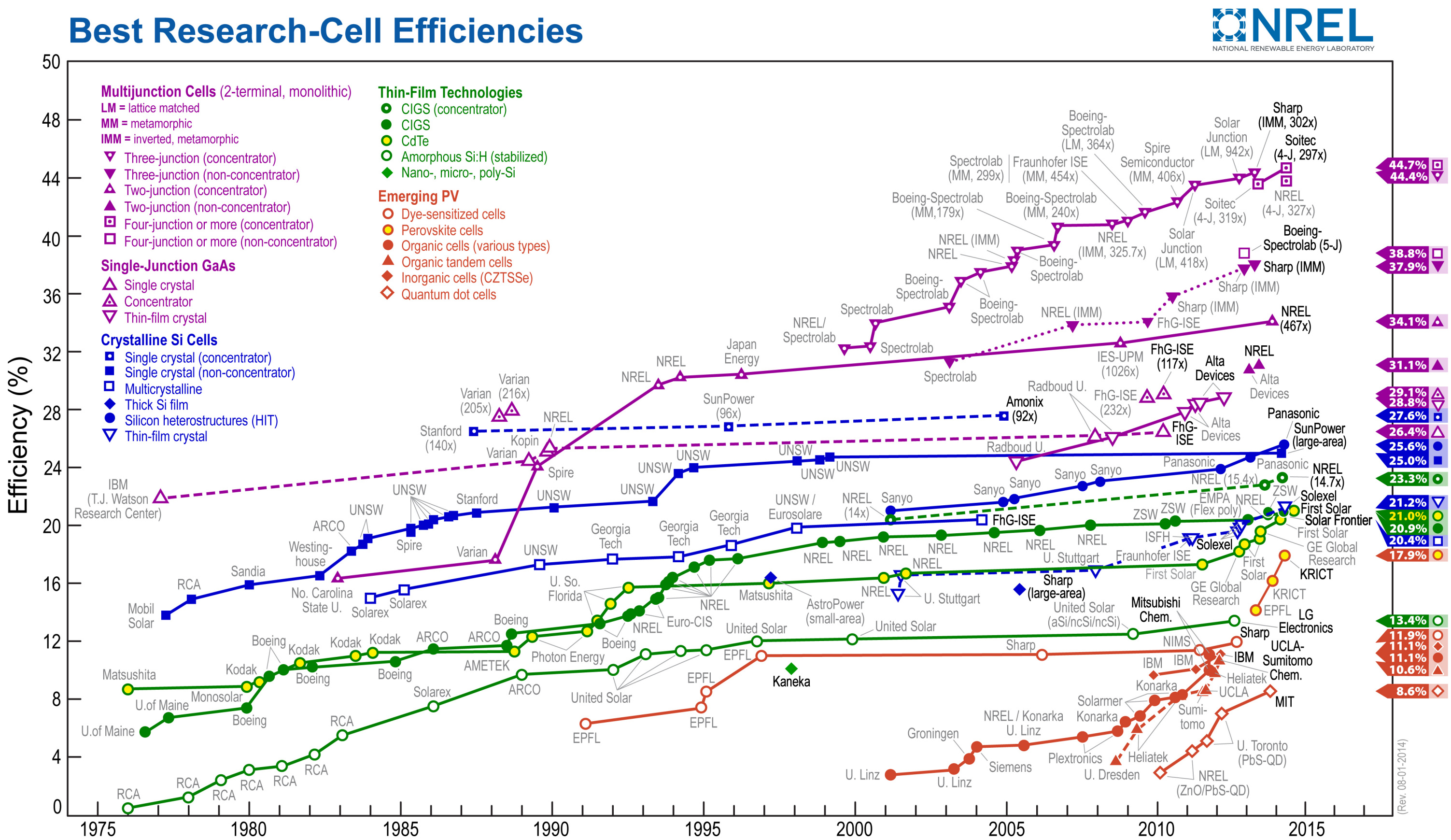

Figure 4.1: The efficiency development of different PV technologies. Source: NREL (2014). Note that this chapter will focus on crystalline silicon cells: single crystalline and multicrystalline, and the thin film technologies CIGS, CdTe and Amorphous Si.

4.1 Crystalline silicon

Crystalline silicon was one of the earliest types of PV cells, and it is by far the most commonly used PV technology. The active material is highly purified silicon, and silicon is after oxygen the most abundant element on the planet. There are two main types of crystalline silicon cells: monocrystalline and multicrystalline. They are composed of different crystalline structures, which are determined early in the manufacturing process (U.S. Department of Energy, 2013).

The molecular structure of monocrystalline silicon is uniform because the entire structure consists of a single crystal. This uniformity is ideal for transferring electrons efficiently through the material (U.S. Department of Energy, 2013). Monocrystalline modules have an efficiency between 15 and 20 per cent, which is the highest among the widely used PV technologies (Maehlum, 2013a). In contrast, multicrystalline silicon consists of many crystals, which create grain boundaries within the material. These boundaries impair the electron flow and hence reduce the power output of the cell (U.S. Department of Energy, 2013). Multicrystalline modules have an efficiency between 13 and 16 per cent, but they are cheaper to produce than monocrystalline modules (Maehlum, 2013a). The manufacturing process of crystalline PV modules, both monocrystalline and multicrystalline, consists of five steps; polysilicon production, wafer production, ingot production, cell production, and finally module assembly. The manufacturing steps are illustrated in Figure 4.2, and each step will be explained in further detail below.

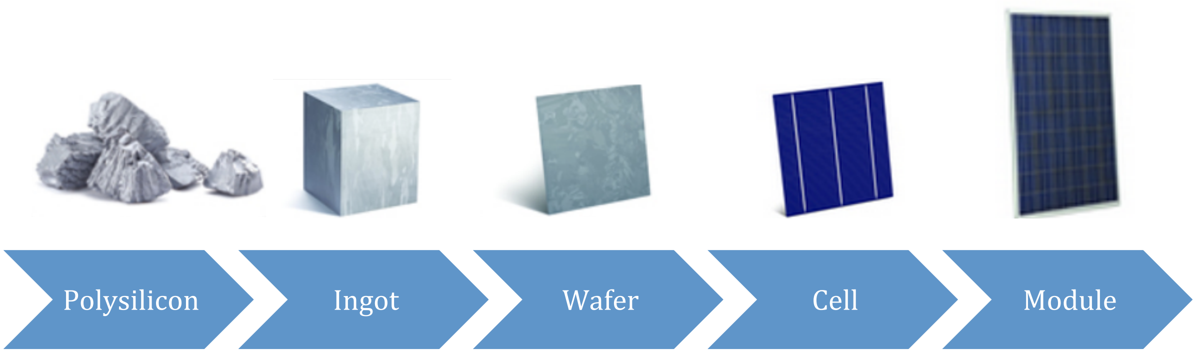

Figure 4.2: The manufacturing steps of crystalline silicon modules. Source: see text.

Polysilicon production

Polysilicon is the main raw material in the production of crystalline PV modules (Thorpe, 2011). During the polysilicon production, silicon is refined into solar-grade polysilicon, which has a purity of 99.9999 per cent. This can be compared with the more expensive electro-grade polysilicon, widely used in the electronics industry, which has a purity of 99.999999 per cent (Green Rhino Energy, 2013). The quality of the polysilicon is essential for the quality of the PV cell and according to Stone & Associates (2011), even a small decrease in module efficiency can offset the potential cost savings from using lower quality polysilicon.

The production of polysilicon is relatively standardised and most producers go about manufacturing largely the same way (Chamness and Tracy, 2011). The production is highly automated and it is the most capital-intensive step of the crystalline silicon PV value chain. The further down the value chain, the less capital intensive the production gets. Process know-how and economies of scale is key for producers of polysilicon.[2] Moreover, polysilicon production requires large amounts of energy. Of the total energy needed to produce a PV module, the polysilicon production accounts for about 50 per cent (Kumar, 2014), see Figure 4.3.

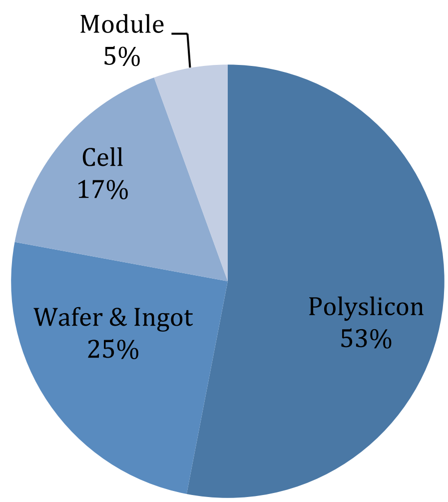

Figure 4.3: The energy required in each step of the value chain. Source: Kumar (2014)
Note: For the module, the required energy does not include components such as glass, frame et cetera.

Ingot and wafer production

In the next step of the production process, ingot production, the crystalline structure is determined. To create a monocrystalline structure, the polysilicon is melted and slowly solidified and grown through a seed into a single crystal ingot (U.S Department of Energy, 2013). The produced ingot has a cylindrical shape but is cut into an octagon to increase module surface usage. There is however a trade-off between surface optimization and low waste of silicon, as much silicon is wasted to cut the edges off the cylindrical ingot (MIT OpenCourseWare, 2014a). To produce a multicrystalline ingot, the melted silicon is usually directly cast into a squared mold and solidified into an ingot. The ingots are diced to obtain the required dimensions. Compared to multicrystalline ingots, monocrystalline ingots are produced with polysilicon of higher purity (U.S. Department of Energy, 2013).

Mono- and multicrystalline ingots are cut into thin slices called wafers. During the slicing, up to 50 per cent of the silicon is wasted. New techniques, such as the ribbon

[2] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

process, have been developed to minimize the waste. In the ribbon process, the wafer can either be grown on a substrate or directly developed by pulling it out of the melted polysilicon. This eliminates an entire step of the value chain as it renders ingot production unnecessary. Due to costs and quality issues, however, this technique is currently not used on a large scale (MIT OpenCourseWare, 2014a).

Both ingot and wafer production are capital intensive, although less so than the polysilicon production. The crystal growing and casting processes require large amounts of energy to power the high temperature operations (Stone & Associates, 2011). Knowledge in materials science as well as technological know-how is required. It is very common for the ingot and wafer production to be vertically integrated.[3] [4] There are several synergies for producers of both ingots and wafers. These can be found within manufacturing processes, in the use of equipment, and in the knowledge required by the staff. Moreover, quality control of multicrystalline ingots is difficult, but if ingot and wafer production is integrated, the quality control can be made on the wafer where more material is visible. [5]

Cell production

Wafers are building blocks in the cell production. In order to remove marks and defects, the wafers undergo a series of cleansing and treatment processes. They are then doped with atoms to improve the semiconducting properties and to give the layers their respective positive and negative potential. An antireflective coating is applied to increase the ability to capture sunlight. The last step of cell production is to create electrical contact by applying thin stripes of metal onto the cells (planete-energies.com, 2012). The efficiency of the PV module highly depends on the efficiency of the cells, and the cell production is therefore one of the most crucial steps in the value chain.[6] However, the main cost-minimizing driver is not increased cell efficiency, but optimization of the manufacturing process. [7] The PV cell is

[3] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

[4] Marco Burkhardt, Managing Director PV Crystalox, Interviewed May 27th 2014

[5] Marco Burkhardt, Managing Director PV Crystalox, Interviewed May 27th 2014

[6] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

[7] Frank Peter, Senior Project Manager Prognos, Interviewed May 21st 2014

furthermore an electronic device and in contrast to previous steps in the value chain, knowledge in electronics and electronic manufacturing is essential. [8]

Module assembly

The last production step of a crystalline silicon PV panel is the module assembly. Cells are assembled and wired together to form a PV module. The cells are inserted between two layers of plastic film, which are heat-bonded together to encapsulate the cells and make the module waterproof. A layer of glass, an insulation plate, and an aluminium frame are added to enhance efficiency and rigidness (planete-energies.com, 2012).

The module assembly is the most labour intensive part of the value chain.[9] The capital cost of module assembly is lower than in the upstream value chain. Therefore, economies of scale, even though present, is of lesser importance and smaller plants can be economically justified (Stone & Associates, 2011). The module assembly further requires knowledge in electronic and mechanical manufacturing (Nexus Energytech, 2012), as well as skills to optimize the assembly. This includes optimizing the logistics of assembly and to put all components together in the most efficient way. Moreover, a module manufacturer needs skills connected to sales and marketing. [10]

4.2 Thin film technologies

Thin film refers to a group of technologies in which micro-thin layers of photosensitive semi-conductive materials are deposited on a low-cost backing (Thorpe, 2011). Depending on which materials that are used, thin film modules can be flexible and thereby used for different applications, such as curved surfaces and buildings and product integration.[11] The micro-thin layers require very small amounts of semi-conductive material, resulting in lower manufacturing costs for thin film modules compared to the more material-intensive crystalline silicon

[8] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

[9] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

[10] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

[11] Stefan Nitzsche, Sales/Marketing Director Solarion, Interviewed May 26th 2014

modules (Thorpe, 2011). A lower energy demand further decreases the costs of thin film manufacturing. Beside the advantages of low manufacturing cost, thin film modules are also more tolerant to shadow and more resistant to high temperatures (Maehlum, 2014). Depending on the specific thin film technology, the modules have an average efficiency between 5 and 13 per cent (EPIA, 2014b), which is significantly lower than that of crystalline silicon modules. Due to its lower efficiency, the thin film technology has had to rely on its lower manufacturing cost to be competitive. [12] The lower efficiency also results in the need of a larger surface area to produce the same output of electricity as crystalline silicon modules. On areas where space is a constraint, such as on rooftops, this is a drawback (Thorpe, 2011).

The manufacturing processes for the main thin film technologies are on a basic level rather similar. First, a very thin layer of photosensitive semi-conductive material is deposited onto a low cost substrate such as glass, stainless steel, or plastic (Thorpe, 2011). This deposition process requires high precision and most deposition techniques can control the thickness of the thin film layer with an accuracy of a few tens of nanometres. To obtain the required precision, most deposition processes are done in vacuum (MIT OpenCourseWare, 2014b). The thin film layer is structured into cells in order to form an electrical circuit, and the cells are wired together and framed. Unlike crystalline silicon modules, the manufacturing process of thin film modules is continuous and it cannot easily be divided into separate steps (Green Rhino Energy, 2013). The manufacturing process of thin film modules is highly automated (U.S. Department of Energy, 2013) and most deposition processes require capital-intensive production equipment. The manufacturing process is not yet as standardised as that of crystalline silicon modules, and for some of thin film technologies there are major manufacturing challenges to overcome (MIT OpenCourseWare, 2014b).

There are three main commercially available thin film technologies on the market today: amorphous silicon, cadmium telluride, and copper indium gallium selenide (CIGS). These are named after their respective active material (Thorpe, 2011), and each technology will described in further detail below.

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[12] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

4.2.1 Amorphous silicon

The material composition of amorphous silicon and crystalline silicon are different. In an amorphous solid, the atoms are not arranged in any particular order. The amorphous silicon does not form crystalline structures and it consists of large numbers of structural and bonding defects. Due to this inherent material structure, amorphous silicon cells have lower efficiency outputs than crystalline silicon cells (U.S. Department of Energy, 2013). In order to increase the efficiency of amorphous silicon modules, new construction techniques have been developed. On technique stacks several amorphous cells on top of each other, each made to absorb a specific frequency of light (Maehlum, 2013b). With this technique the modules reaches an efficiency of between 6 and 8 per cent (Maehlum, 2013a). Besides the low efficiency, another drawback of amorphous silicon cells is that they are rather unstable. The cell efficiency decreases over time when exposed to sunlight. After some time, the efficiency stabilizes but on a lower level (U.S. Department of Energy, 2013). The advantages of the technology include its low manufacturing cost, and that is relies on silicon, with an almost unlimited supply of raw material.[13]

Amorphous silicon used to be the most common thin film technology with over 90 per cent of the thin film market in the early 2000's (Fraunhofer ISE, 2013). The drawbacks of the amorphous silicon thin film technology, the low efficiency in particular, have decreased its market share as other technologies have gained momentum. Currently, amorphous thin film modules are only manufactured on a small scale and some believe that it has been outcompeted altogether.

4.2.2 Cadmium telluride

Cadmium telluride has the largest market share among thin-film technologies. It has a stable polycrystalline structure formed by cadmium and tellurium (Maehlum, 2014). The efficiency of cadmium telluride modules is between 9 and 11 per cent, which is higher than for amorphous silicon modules but slightly lower than the crystalline silicon modules (Maehlum, 2013a). The main advantage of cadmium telluride modules is their low manufacturing cost. First Solar, the largest producer

[13] Stefan Gall, Senior Scientist Helmholtz-Zentrum Berlin, Interviewed May 23rd 2014

of cadmium telluride modules, have made efforts to improve the manufacturing processes and have managed to overcome many difficulties related to thin film manufacturing. The cost per watt of a cadmium telluride module is today competitive with the cost per watt of a crystalline module (MIT OpenCourseWare, 2014b). Moreover, cadmium telluride modules experience less efficiency drops in high temperatures than crystalline silicon modules. This increases the competitiveness of cadmium telluride modules in areas with warm climate (Maehlum, 2014).

A drawback of the technology is that it is reliant on cadmium, which is a hazardous material, and on telluride, which is a relatively scarce material. The use of cadmium is restricted within the EU and it is banned in Japan (MIT OpenCourseWare, 2014b). However, as long as the cadmium telluride compound is contained within the PV module, the threat of its toxicity is very low. The use of cadmium can complicate the marketability of the modules as well as result in costly and sometimes dangerous disposal and recycling processes (Maehlum, 2014). A shortage of a critical material, such as telluride, could increase the production cost of cadmium telluride modules. In the long-term it can also cap the growth potential of the cadmium telluride technology (Andersson, 2000).

4.2.3 CIGS

CIGS has a polycrystalline structure composed by copper, indium, selenium, and/or gallium. It has a commercially available module efficiency of between 10 and 12 per cent (Maehlum, 2013a), but in laboratory tests the technology has reached the highest cell efficiency of all thin-film technologies; 20.9 per cent (NREL, 2014). The large gap between the commercially available module efficiency and the lab efficiency is related to the difficulties to manufacture CIGS modules on a large scale. The challenges concern difficulties of achieving a uniform large-scale deposition and to avoid defects in interfaces of different material layers. These interfaces are complex and still poorly understood (MIT OpenCourseWare, 2014c).

A drawback of the CIGS technology is that it is based on indium, which is a scarce metal. There is also a growing use of indium in other industries, which can expedite a shortage and hence a price increase of the metal (EPIA, 2013). CIGS modules also contain cadmium, but in a smaller amount compared to cadmium telluride modules (Maehlum 2013a). However, current research aims to remove the use of cadmium in CIGS modules (MIT OpenCourseWare, 2014c).

5. Applications and the downstream value chain

This chapter presents the most common PV system applications and describes the downstream PV value chain.

5.1 Application areas

The PV market is rather heterogeneous and which PV applications that are most common tend to vary between different markets.[14] PV modules are normally installed on rooftops, as ground-mounted systems, or integrated into buildings or smaller products. Of these three, rooftop installations and ground-mounted systems are by far more common (EPIA, 2014a). Rooftop installations have been common in nations such as Germany and Japan, and generally refer to installations that supply residential households with electricity (Johnstone, 2011). It is not uncommon, however, to see rooftop installations on commercial or industrial buildings as well. The average ground mounted system tends to be a power plant, significantly larger than a rooftop installation, that supplies a national grid or an industrial facility with electricity. In this case, after having studied the content of annual reports of various firms (see Appendix I), it has been concluded that the system owner is rarely an individual but more likely a utility or an industrial investor.

All PV systems can be either grid-connected or installed off-grid. Grid-connected systems allow the system owner to feed electricity surplus into the grid or use backup electricity from the grid when needed. Off-grid systems tend to be used in remote areas or in locations the national grid has difficulties reaching. A PV system consists of other components besides PV modules. These are usually referred to as system components and include inverters, storage solutions, system charge controllers, and balance of systems components. Depending on the application of the PV system, different components are needed (Thorpe, 2011). Off-grid systems, for instance, require a battery or another form of storage solution to store the produced electricity (EPIA, 2010). The early applications of PV modules were mainly off-grid installations, but on-grid applications have dominated the PV market since the mid 1990's (IEA, 2013).

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[14] Oliver Lyncker, Director Marketing and Business Development Phoenix Solar, Interviewed June 2nd 2014

5.2 The downstream value chain

The downstream value chain refers to the remaining activities that need to be carried out before the PV module reaches its final consumer. There is a wide range of actors performing these services. Some actors are specialized in one part of the downstream value chain, while others are vertically integrated (concluded after studying content listed in Appendix I). Fully integrated actors performing all steps in the downstream value chain are usually referred to as system integrators (Gifford, 2012). The linkage between the module manufacturer and the eventual system owner often involves a network of national and international distributors and wholesalers (concluded after studying content listed in Appendix I) The main activities within the downstream value chain are project development, finance, design and engineering, construction and commissioning, and operation and maintenance (Scatec Solar, 2014), see Figure 5.1. The progression of these activities is not strictly linear and the amount of time and money required for each activity depends on the size and application of the PV system (IFC, 2012).

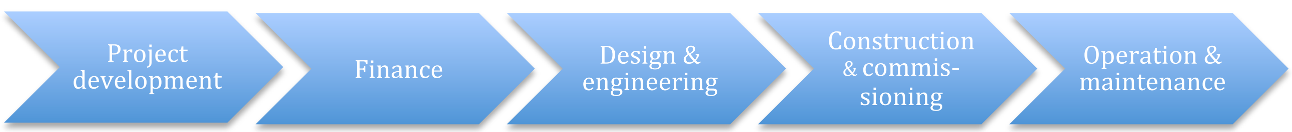

Figure 5.1: The downstream value chain of a PV module. Source: see text.

Project development includes activities such as power purchase agreements, site assessment, obtaining project permits and project finance (First Solar, 2014a; EnergyTrend, 2012). As the system size increases, so does the complexity of the project development (EnergyTrend, 2012). Large PV system projects are usually financed on a project finance basis (IFC, 2012). The equity or project finance partner often has much to say when it comes to designing the project.[15] The financing and the cost of capital has a large impact on the total cost of the PV system. The impact the financial terms have on the total cost of ownership is sometimes larger than the cost of modules, project development, and operation and maintenance taken together (First Solar, 2014b). Design and engineering aim to achieve a low levelized

[15] Stefan Müller, Member of the Board/ Chief Operating Officer, Enerparc, Interviewed May 19th 2014

cost of electricity for PV systems. Every site is different in terms of geographical location, solar radiation, grid connection et cetera. This is all taken into account to optimize the output of the PV system. When the design is completed, the physical construction and installation is carried out (IFC, 2012). For residential PV systems, the activities related to construction and commissioning tend to be carried out by local actors whereas large-scale installations tend to be done by both national and international actors (EnergyTrend, 2012). It is rather common to vertically integrate design and engineering with construction and commissioning. Such firms are referred to as engineering, procurement, and construction (EPC) firms (concluded after studying content listed in Appendix I). Compared to many other power generating technologies, PV systems require relatively little maintenance and services. However, facility monitoring, module cleaning, breakdown management, and reparation work are needed in order to optimize the energy yield and to ensure a long lifetime of the PV system (IFC, 2012).

In the downstream PV value chain, it is generally considered an advantage to be close to the end user and to have a local footprint. This makes system integration and installation services more likely to be supplied by local firms. [16] The downstream steps of the PV value chain have lower barriers to entry than the upstream steps, much due to lower capital requirements.[17] The benefits from economies of scale are relatively low and mostly related to discounts in bulk purchases of modules and other system components. Hence, even if a certain volume is required to be profitable, the decreasing scale benefits allow smaller firms to compete. [18]

[16] Oliver Lyncker, Director Marketing and Business Development Phoenix Solar, Interviewed June 2nd 2014

[17] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

[18] Oliver Lyncker, Director Marketing and Business Development Phoenix Solar, Interviewed June 2nd 2014

6. Historical development

This chapter outlines key events in the development of the PV industry the past 15 years. The sub-chapters describe these events and their effects in detail. Throughout the chapter, theory is used to analyse the events and characteristics of the PV industry.

Figure 6.1 presents a timeline, marking the events and developments that will be described in the following sub-chapters. Some events can be narrowed down to a specific date or year, while others span several years and might have diffuse starting and end points.

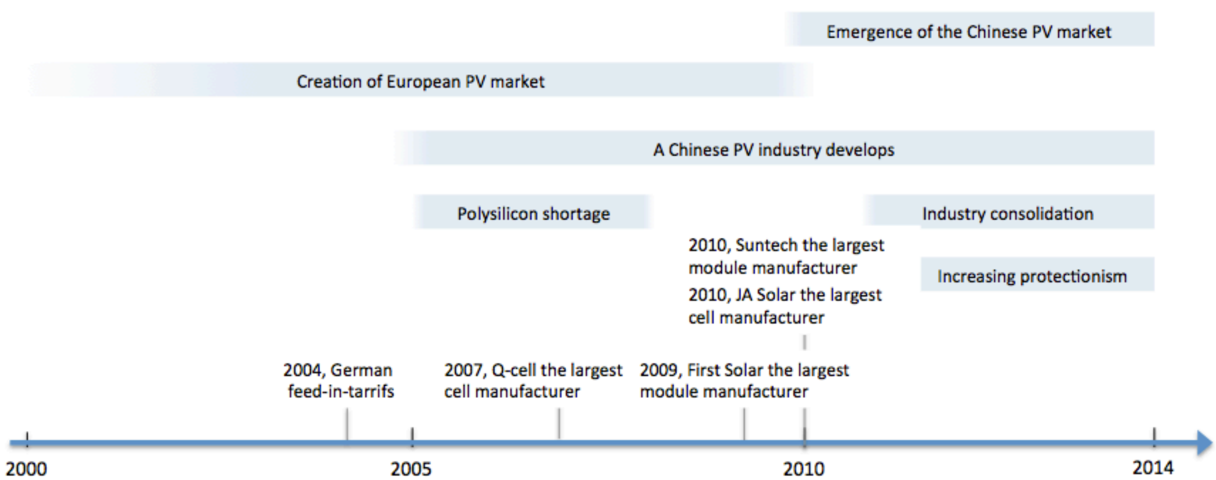

Figure 6.1: Timeline indicating important events in the PV industry. Sources: see text.

6.1 Creation of a European PV market

The use of PV modules is most beneficial where the sun shines the most (Thorpe, 2011). Germany is not such an area. Yet it is here the PV market and industry started to experience the exponential growth that has created the PV industry of today. What always is brought forward as the main driver of the PV industry development is the German feed-in tariff.[19, 20]

[19] Stefan Gall, Senior Scientist Helmholtz-Zentrum Berlin, Interviewed May 23rd 2014

[20] Stefan Müller, Member of the Board/ Chief Operating Officer, Enerparc, Interviewed May 19th 2014

When the 100,000 roof top program was launched in Germany in 1999 (Johnstone, 2011), it was the largest PV program in history and it gave strong financial support to homeowners who invested in PV (Siemens, 1999). Moreover, the German Renewable Energies Law, or the EEG, was voted into law in 2000. The EEG was a technology specific policy instrument that included the initial feed-in tariff. The 100,000 rooftop program and the EEG made PV systems attractive as an investment (Johnstone, 2011). When the program ended, a market had been created and the PV technology had been proven to work. The EEG was revised and in 2004, the feed-in tariff for PV was increased and created a surge for PV systems in Germany.[21] The German PV installations increased from 150 megawatts in 2003 to 600 megawatts in 2004 (EPIA, 2014a), see Figure 6.2.

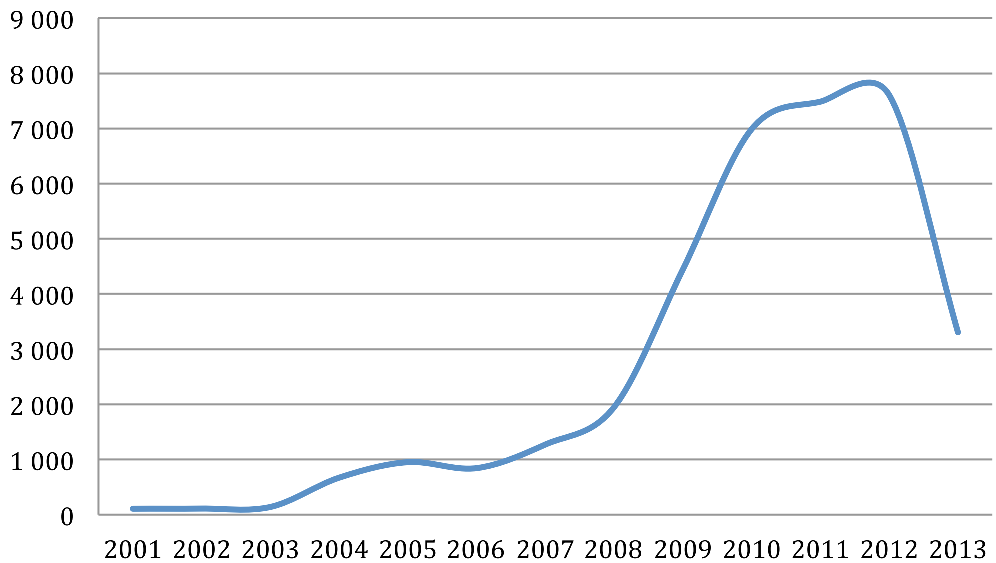

Figure 6.2: Annual PV instalments in Germany, 2001-2013, in megawatts. Source: Roney (2014)

Other European countries followed Germany's example of feed-in tariffs for solar power. Spain's feed-in tariff was similar to the German. With the country's large sun exposure, PV became a very attractive investment and the market exploded. The three-year goal of 400 megawatts installed capacity was reached in three months. In contrast to Germany, the Spanish mostly installed ground-mounted power plants. The surge for PV in Spain became difficult to control and the feed-in tariffs were cut in 2008, resulting in a collapse of the Spanish market. Other countries that mimicked

[21] Gerhard Willeke, Coordinator PV Fraunhofer ISE, Interviewed June 3rd 2014

Germany's feed-in tariff include Italy, the UK, and the Czech Republic (Johnstone, 2011).

The German feed-in tariff created a market for PV modules, which attracted firms that were keen to profit from the increasing popularity of PV systems. This led to that many firms tried to build a business connected to the PV value chain, often with new technologies. [22] After the EEG was first introduced in 2000, firms slowly started entering the PV industry and by 2006-2007 the number of PV firms in Germany grew rapidly.[23] The accelerating sales and the many entrants suggest that the PV industry at this time was entering the growth stage of its industry life cycle. Up until this point, Japan and the US had been among the world's top producers in the PV industry. The sales there however kept shrinking and a couple of the largest US producers went bankrupt in the early 2000's. With the German industry coming up, Japan saw its share of the global PV market drop from 45 to 25 per cent between 2005 and 2007 (Johnstone, 2011).

In the beginning of the 2000's, most of the newcomers in the German PV industry were entrants. The market, even though growing, was too small for large corporations.[24] The market dynamics in the early PV industry further required speed and flexibility, which is not something incumbents tend to do well.[25] Q-Cells was a German entrant founded as a specialized producer of high-quality crystalline silicon cells. The cell production commenced in 2001 and the production capacity increased steadily. Q-Cells became the fastest growing company in Germany and in 2007 it overtook Japanese Sharp as the world's top cell producer (Johnstone, 2011). As the production was ramping up in Germany, there was an increasing need for automated production equipment. The manufacturing equipment became more and more standardised for crystalline silicon cell and module manufacturing[26] and by 2008-2009, German equipment manufacturers supplied tools for every step of the

[22]Stefan Nitzsche, Sales/Marketing Director Solarion, Interviewed May 26th 2014

[23] Thomas Grigoleit, Director Energy, Environment, and Resources German Trade and Invest, Interviewed May 22nd 2014

[24] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

[25] Stefan Müller, Member of the Board/ Chief Operating Officer, Enerparc, Interviewed May 19th 2014

[26] Stefan Gall, Senior Scientist Helmholtz-Zentrum Berlin, Interviewed May 23rd 2014

PV value chain (IEA, 2010). This is another sign that the industry was in the growth stage, as increasing manufacturing efficiency is a common trait of the growth stage. The German PV firms used mainly German equipment manufacturers who developed new equipment, sometimes on their own and sometimes in cooperation with PV firms. This led to a large increase in productivity, and as a result, outputs increased ten folds.[27]

In the area in the east of Germany where Q-Cells chose to locate, other start-ups set up close-by (Johnstone, 2011). Q-Cells invested heavily in some of these firms, broadening its technology scope from crystalline silicon to thin film technologies such as amorphous silicon, cadmium telluride, polycrystalline silicon and CIGS.[28,29] The fact that firms were investigating, researching, and trying out several technologies simultaneously indicates that even though the crystalline silicon technology was dominant, speculations around and investments in a future technology shift were frequent. Hence, the PV technology was in this sense in the fluid phase of the technology life cycle. Q-Cells and its different subsidiaries was the beginning of what became known as Solar Valley, which soon would incorporate three quarters of Germany's many PV-related firms and businesses (Johnstone, 2011). International firms also chose to locate in Germany at this time. First Solar, for instance, was in 2006 offered incentives to locate a production plant in the country. First Solar's sales in Europe were very strong. In 2008, the European sales made up 94 per cent of its revenues (Johnstone, 2011).

With the German EEG followed a guarantee that an investment in solar would pay off. Even if other markets also grew, the Japanese PV market for instance doubled in size between 2003 and 2007, the German market exploded and the production capacity increased nine fold (Johnstone, 2011). The demand was significantly larger than the available supply, leading to large profits for firms in the entire value chain. The big increase in demand had resulted in a lack of modules.[30] Again, this points to

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[27] Frank Peter, Senior Project Manager Prognos, Interviewed May 21st 2014

[28] Stefan Gall, Senior Scientist Helmholtz-Zentrum Berlin, Interviewed May 23rd 2014

[29] Martin Meilchen, Director Product Management Solibro, Interviewed May 28th 2014

[30] Thomas Grigoleit, Director Energy, Environment, and Resources German Trade and Invest, Interviewed May 22nd 2014

that the industry was in the growth stage, as industries in this stage often experience undersupply. Start-ups in PV could have very high valuations and the focus was to improve the technologies (Aanesen, Heck, and Pinner, 2012). The rapid growth further led to increased efficiency and lower costs.[31] The European feed-in tariffs had created the largest PV market in the world. By 2007, Europe accounted for 70 per cent of the global PV market (Johnstone, 2011).

6.2 A global polysilicon shortage

In the early 2000's, the PV market grew rapidly. Between 2000 and 2005, the global cumulative installed PV capacity increased from 1.3 to 5.1 gigawatts (EPIA, 2014a). The German feed-in tariff had successfully created a market for PV modules and many companies were entering the industry (Johnstone, 2011). The supply had difficulties keeping up with the demand, and bottlenecks occurred in different parts of the PV value chain. One of the most severe bottlenecks was the lack of polysilicon between 2005 and 2008, resulting in a tenfold price increase of the most important raw material, see Figure 6.3.

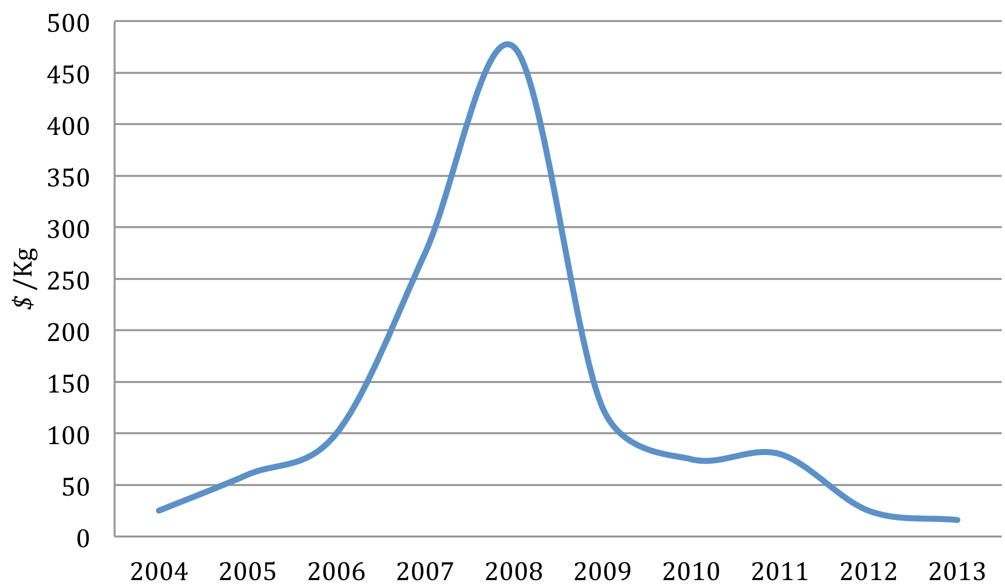

Figure 6.3: The spot price development of polysilicon. Source: The Washington Post (2013)

[31] Anil Vijayendran, Senior Director, Product Management MiaSolé, Interviewed at Intersolar June 4th 2014

Previously, much of the polysilicon used for PV cells had been electro-grade polysilicon produced for the electronic industry (Price and Robert, 2010).[32] During 2007, however, the polysilicon demand from the PV industry surpassed that of the electronic industry and since then the PV industry has been the main driver of growth in polysilicon production (Price and Robert, 2010). Producing polysilicon requires capital-intensive facilities and the construction lead-time is long. The PV market had been driven by subsidies, making many polysilicon producers unsure of future market developments. As a result, large investments were put on hold. At a time when the demand for PV modules increased rapidly, the lack of investments in polysilicon production plants led to an undersupply of polysilicon starting in 2005.[33]

Polysilicon is sold both through long-term contracts and on the spot market. During the steep price increases from 2005 to 2008, many PV firms tried to secure their polysilicon supply by signing long-term contracts to fixed prices.[34] Many German PV firms were successful in the negotiation of these long-term contracts,[35]and they gained cost advantages over firms that had to purchase polysilicon on the spot market to a substantially higher price (Stone and Associates, 2011). According to Johnstone (2011), one of the main reasons why Sharp lost its leading position in the PV industry was that the firm failed to negotiate such long-term contracts. When the polysilicon price peaked in 2008, the cost of polysilicon represented 71 per cent of the total module cost for Chinese module manufacturers. This cost share had been reduced to 18 per cent by the end of 2013. The lower share of polysilicon cost did however not only relate to lower polysilicon prices but also to thinner wafers and less unit consumption because of advances in production techniques (Mehta, 2014a).

The polysilicon shortage affected firms in the entire PV value chain and the lack of raw material led to an undersupply of crystalline PV modules.[36] When the

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[32] Marco Burkhardt, Managing Director PV Crystalox, Interviewed May 27th 2014

[33] Stefan Gall, Senior Scientist Helmholtz-Zentrum Berlin, Interviewed May 23rd 2014

[34] Frank Peter, Senior Project Manager Prognos, Interviewed May 21st 2014

[35] Gerhard Willeke, Coordinator PV Fraunhofer ISE, Interviewed June 3rd 2014

[36] Thomas Grigoleit, Director Energy, Environment, and Resources German Trade and Invest, Interviewed May 22nd 2014

polysilicon price was high, many PV firms invested in technologies aimed at minimizing the use and waste of polysilicon. There were for instance large economic incentives for the development and use of technologies such as the ribbon process for wafer manufacturing (MIT OpenCourseWare, 2014a).[37] During the shortage, there were also increased investments in other PV technologies such as thin film. The high polysilicon price further increased the difference in manufacturing costs between thin film and crystalline silicon modules. As a result, the global market share of thin film technologies increased from around five per cent in 2005 to around 15 per cent in 2008 (Willeke, 2013). In 2009, First Solar had, as the first thin film manufacturer in history, taken over the lead as the largest module manufacturer in the world (Mints, 2014).

For polysilicon producers, long-term contracts with PV firms were a security for the large investments needed to increase capacity.[38] From 2005, existing polysilicon producers along with many entrants invested heavily in new production facilities. In the past, the main polysilicon producers were located in Germany, Japan, and the US. A large share of the increased capacity investments were made by German and US firms alongside many Asian firms located mainly in China and South Korea (Chamness and Tracy, 2011), see Figure 6.4. To secure their polysilicon supply and benefit from the high margins, several PV firms also vertically integrated upstream.[39][40] The strategic challenges of polysilicon production compared to those of cell or module production are rather different in terms of the volumes, capital, and competence required, which speak in favour of division of labour. Hence, the fact that PV firms integrated upstream and entered the polysilicon segment at this time shows the importance of securing the polysilicon supply at a reasonable price. Moreover, one can argue that the polysilicon shortage created an unstable external environment, which increased transaction costs for firms in the PV industry, making vertical integration more beneficial. Many of the new facilities came into operations during 2008-2010, resulting in oversupply (Price and Robert, 2010). At the same

[37] Stefan Gall, Senior Scientist Helmholtz-Zentrum Berlin, Interviewed May 23rd 2014

[38] Mathias Bremer, Director Strategic Marketing Wacker, Interviewed May 30th 2014

[39] Thomas Grigoleit, Director Energy, Environment, and Resources German Trade and Invest, Interviewed May 22nd 2014

[40] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

time, the demand for PV modules decreased due to the financial crisis and cutbacks in several PV subsidy programs (Yingli Solar, 2013; Chamness and Tracy, 2011).

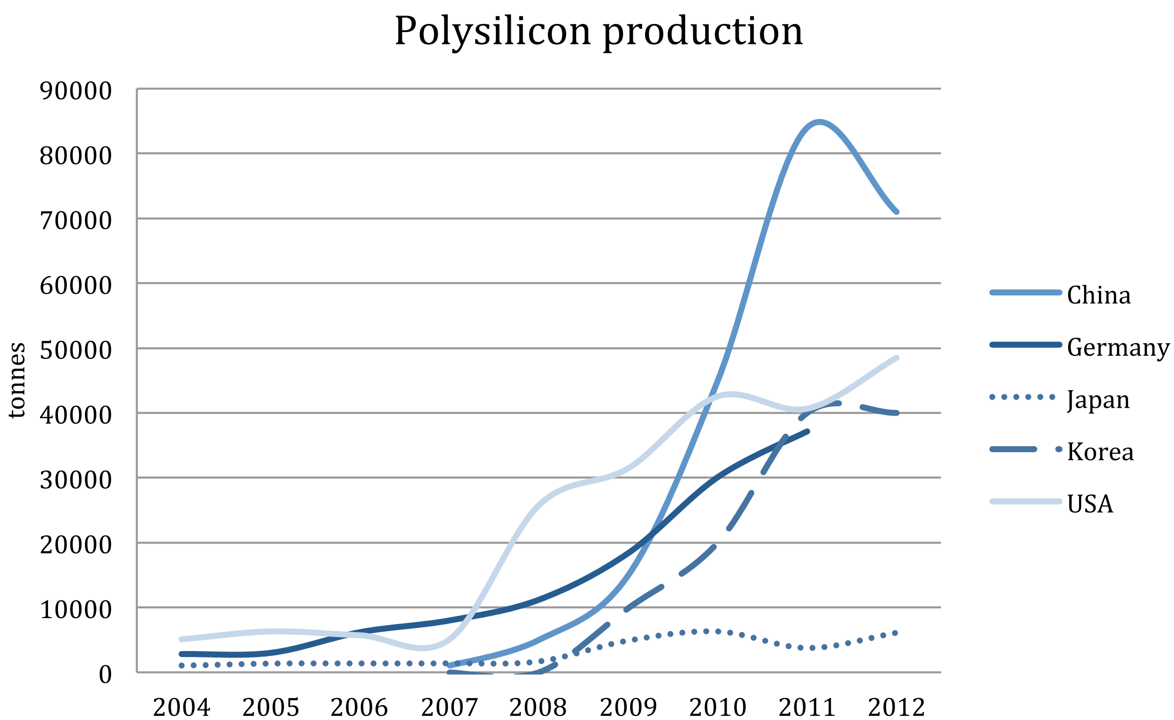

Figure 6.4: Production of polysilicon per country 2004-2012. Source: IEA (2005-2013)

The overcapacity of polysilicon increased the competition among the polysilicon producers and significant price drops followed (Yingli Solar, 2013). Polysilicon production is capital intense and economies of scale is key. Small plants that were economically justified with high polysilicon prices could no longer compete with the large-scale plants. Therefore, many small-scale producers, established around 2005 or 2006, went bankrupt and several of the PV firms that had integrated into polysilicon production sold or closed their facilities.[41] The Chinese cell producer Yingli Solar was one of the PV firms that integrated upstream into polysilicon production. Yingli Solar still owns its polysilicon production facility, but due to low polysilicon prices it is not cost efficient to operate (Yingli Solar, 2013).

Due to the overcapacity and price decrease, investments aimed at minimizing the use and waste of polysilicon declined. The economic incentives were not large

[41] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

enough.[42, 43] For the thin film technologies, the manufacturing costs were still lower than for crystalline silicon. The price drops of crystalline modules, however, made the cost difference too small to make up for the lower efficiency of thin film modules. Therefore, thin film technologies failed to attract the same amounts of investments as during the polysilicon shortage.[44]

6.3 A Chinese PV industry develops

Until the mid 2000's, the majority of the world's PV module demand was supplied by German, Japanese and US firms (IEA, 1999-2009). Local firms such as Q-Cells and SolarWorld were unable to supply the European demand. Actors in the downstream value chain had to look elsewhere for modules and China became an important supplier (Johnstone, 2011). Between 2000 and 2012, the Chinese wafer, cell, and module production increased from only a few megawatts to over 20 gigawatts each (IEA, 1999-2013), see Figures 6.5, 6.6 and 6.7.

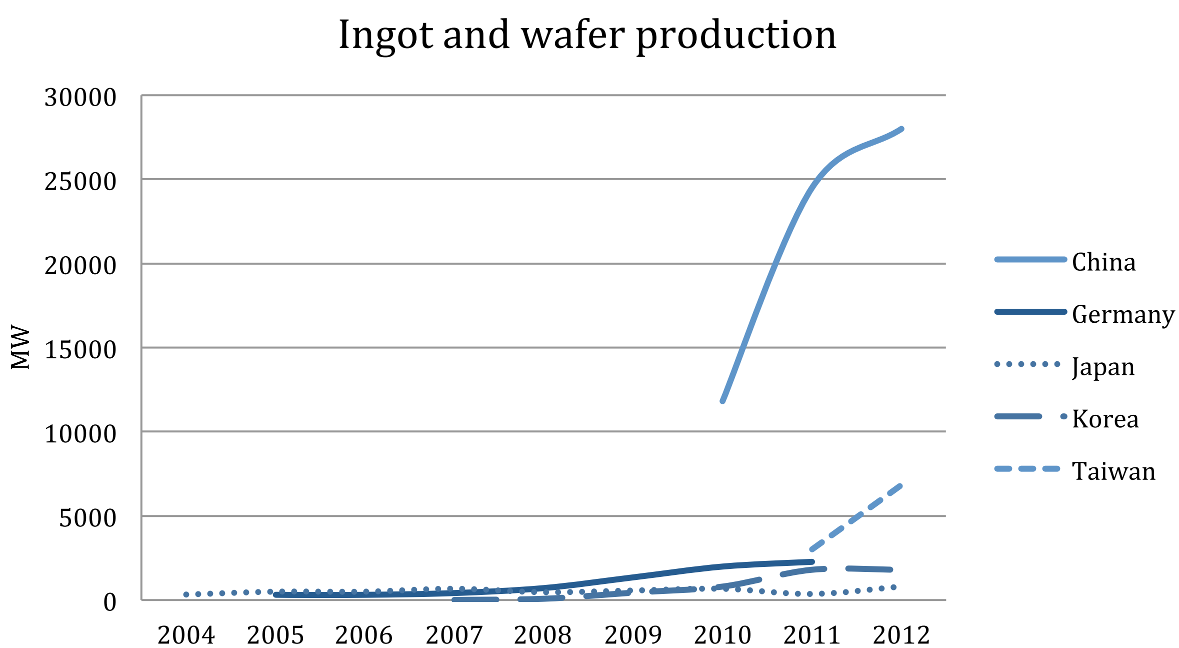

Figure 6.5: Production of ingots and wafers per country 2004-2012. Source: IEA (2005-2013)
Note: Assuming 12 tonnes of ingots equivalent to 1 MW PV cells

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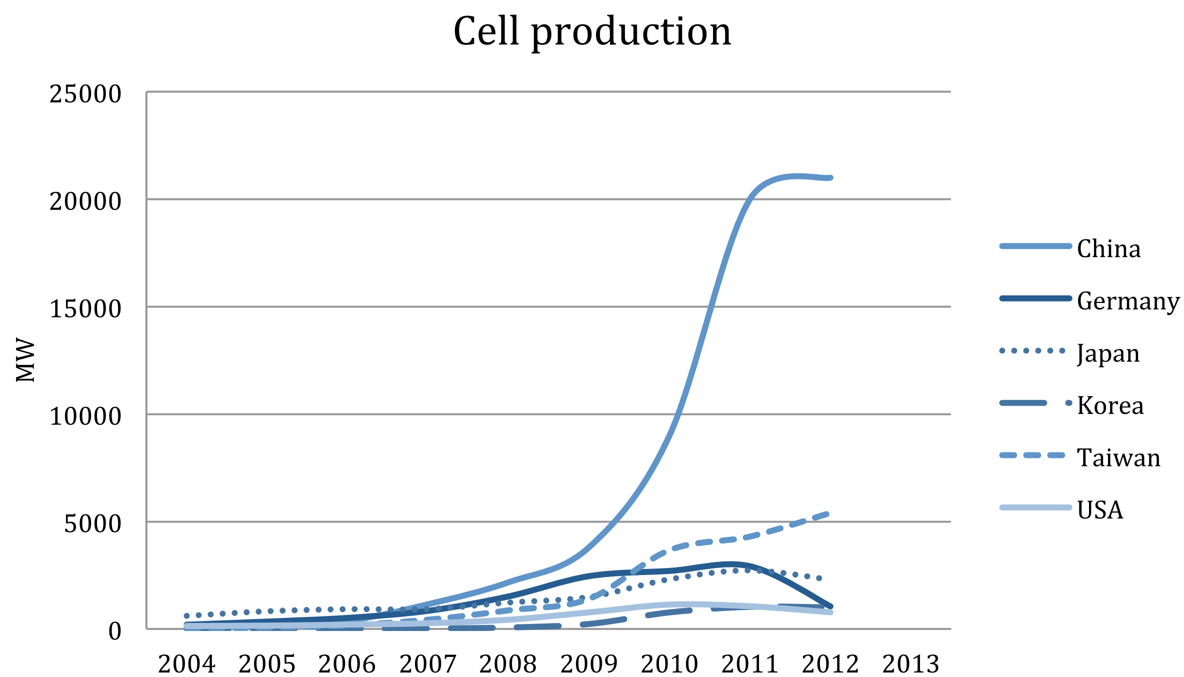
[42] Stefan Gall, Senior Scientist Helmholtz-Zentrum Berlin, Interviewed May 23rd 2014

[43] Martin Meilchen, Director Product Management Solibro, Interviewed May 28th 2014

[44] Martin Meilchen, Director Product Management Solibro, Interviewed May 28th 2014



tion of cells per country 2004-2012. Source: IEA (2005-2013)

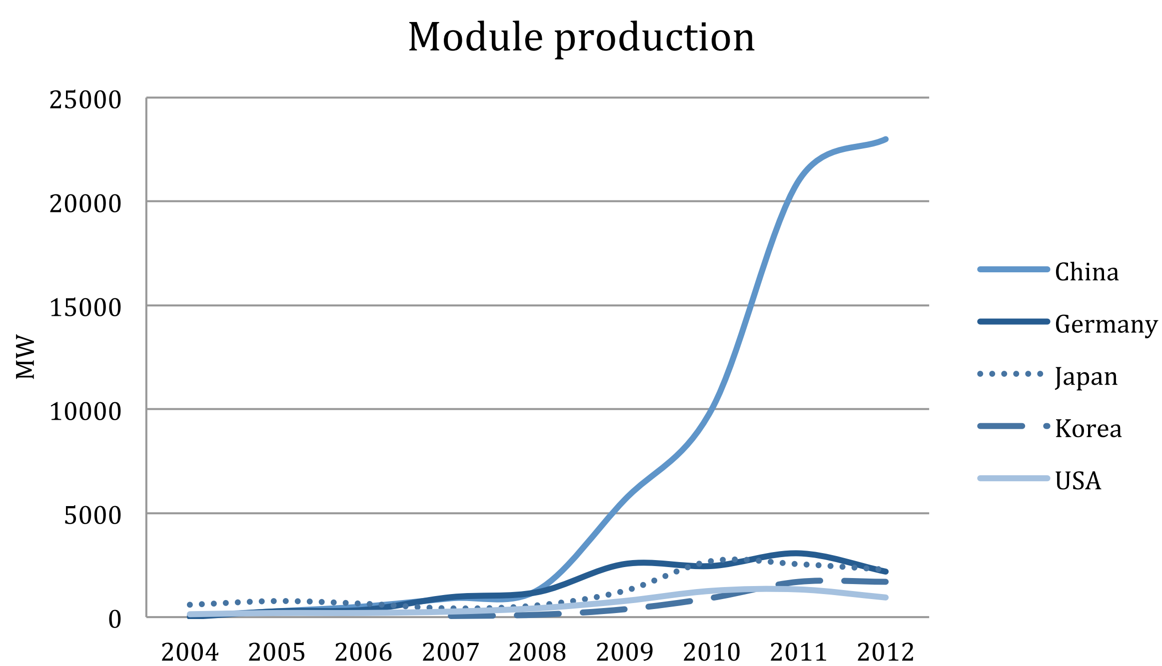


Figure 6.7: Production of modules per country 2004-2012. Source: IEA (2005-2013)

The Chinese PV industry came about as a result of the directed efforts of a government that had decided to support local manufacturing and R&D in the PV sector (Sun et al, 2014; Zhao et al, 2013). The Chinese government started to actively support the development of a PV industry in China in 2000 (Sun et al, 2014). Not only has the Chinese government supported the local PV industry with laws, regulations, and incentive programs. It has also invested directly in various local PV-related firms and projects (Zhao et al, 2013). This stands in contrast to the German subsidies, which subsidised modules regardless of where they came from in order to create a market for PV.[45]

The parts of the PV value chain that first were produced in China on a large scale were crystalline silicon cells and modules.[46] Early on, however, the domestic module production was larger than the cell production, and Chinese module manufacturers were reliant on imported cells mainly from Germany, Japan and the US (IEA, 2004-2006). To set up production facilities for PV cells and modules require lower capital investments[47] and shorter construction time compared to the steps further upstream in the value chain.[48] Of the hundreds of firms that entered the PV industry in China, a majority were module manufacturers whereas the second most common was to enter as a cell producer (China Greentech Energy, 2011).

The first company to produce PV cells in China on a large scale was Suntech.[49] The company was founded in 2001 (Johnstone, 2011), and similar to Q-Cells, began its operations as a cell producer and later integrated vertically into module production.[50] In 2002, Suntech opened a production line with a capacity of 10 megawatts. Compared to the 2.5 megawatts output of the entire Chinese industry the previous year, this was a large increase. The scale allowed cost advantages and by 2003, Suntech's modules were priced far below the average market price while maintaining a 20 per cent profit margin (Johnstone, 2011). Other Chinese PV firms set up around this time that grew to be some of the top cell and module producers in

[45] Martin Meilchen, Director Product Management Solibro, Interviewed May 28th 2014

[46] Gerhard Willeke, Coordinator PV Fraunhofer ISE, Interviewed June 3rd 2014

[47] Bernd Rau, Senior Vice President Roth & Rau, Interviewed May 27th 2014

[48] Thomas Grigoleit, Director Energy, Environment, and Resources German Trade and Invest, Interviewed May 22nd 2014

[49] Stefan Gall, Senior Scientist Helmholtz-Zentrum Berlin, Interviewed May 23rd 2014

[50] Stefan Gall, Senior Scientist Helmholtz-Zentrum Berlin, Interviewed May 23rd 2014

the world include Yingli Solar and Trina Solar, who both started with module production, and JA Solar, who began as a cell producer (Yingli Solar, 2013; Trina Solar, 2013; JA Solar, 2013).

When the German EEG was revised and the feed-in tariff increased, the subsequent rise in European demand of PV modules became a key target for the Chinese firms. Many firms invested in increased capacity to supply the rapidly increasing demand and to keep costs down through economies of scale (Sun et al, 2014). After 2004, many Chinese firms entered the PV industry and just as in Germany, most of them were newly established firms.[51] High entry rates and investments to increase capacity are characteristics of the growth stage of the industry life cycle, and so the PV industry was arguably in the growth phase in China as well as in Germany at this time. In 2007, China became the top cell-producing nation in the world (IEA, 2007-2008). Mass production is generally a sign that an industry has settled on a dominant design and entered the transitional phase of the technology life cycle. Hence, the PV industry was in the growth stage of the industry life cycle and in the transitional phase of the technology life cycle, which according to Grant (2010) are closely connected.

Between 2008 and 2011, the large Chinese firms kept expanding their capacity (Aanesen, Heck, and Pinner, 2012). In 2010, the Chinese firms JA Solar and Suntech took over as the world's largest cell and module producers (Stuart, 2011). The Chinese expansion resulted in annual module price declines of 40 per cent (Aanesen, Heck, and Pinner, 2012). The declining module prices opened up for applications that had previously not been economically viable and the market for PV hence grew larger.[52] Production of other parts of the PV value chain also started to take off in China. Until 2006, the Chinese PV firms imported close to all polysilicon they needed. Since 2009 however, after the polysilicon shortage had driven massive capacity investments in polysilicon facilities, about half of the Chinese PV firms' demand has been supplied domestically (Sun et al, 2014). The Chinese wafer production has increased significantly since 2009 and China has since 2010-2011 been the top wafer producer in the world (IEA, 2010-2012).

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[51] Gerhard Willeke, Coordinator PV Fraunhofer ISE, Interviewed June 3rd 2014

[52] Adrian Honey, Head of Marketing Lorentz, Interviewed May 20th 2014

One of the enabling factors for the rapid capacity increase by the Chinese PV firms was availability of already developed turn key-lines, partly supplied by German equipment manufacturers. The same equipment manufacturers that sold machines to Q-Cells and SolarWorld in Germany started to supply Chinese firms with largely the same equipment.[53] The equipment manufacturers made turn-key manufacturing lines available, which were quickly sold and put into operations (China Greentech Initiative, 2011). Soon, the Chinese firms became the largest customers to the European equipment manufacturers. Hence, much of the European know-how connected to process development within the crystalline silicon technology was transferred to China.[54]

Other reasons for China's success as a PV manufacturing nation include generally low cost structures and high flexibility of the local supply chain. The low cost structure regards most costs of a manufacturer, including costs of capital, energy costs, labour costs, and lower environmental requirements.[55] This is a large advantage since price is an important factor throughout the PV value chain.[56] China also has a highly flexible supply chain, and many suppliers have the capacity and speed to deliver within short notice.[57] For PV cell manufacturing, the knowledge base established around the already existing value chain for electronics in China provided a competitive edge in the PV industry.[58] A final important key to success is that the Chinese firms went for scale. Economies of scale has proven to be important in order to drive down costs in the PV value chain, providing the Chinese firms with a major cost advantage against their international competitors.[59][60]

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53 Gerhard Willeke, Coordinator PV Fraunhofer ISE, Interviewed June 3rd 2014

54 Gerhard Willeke, Coordinator PV Fraunhofer ISE, Interviewed June 3rd 2014

55 Frank Peter, Senior Project Manager Prognos, Interviewed May 21st 2014

56 Mirko Held, Head of Product Management Centrosolar, Interviewed May 19th 2014

57 Adrian Honey, Head of Marketing Lorentz, Interviewed May 20th 2014

58 Frank Peter, Senior Project Manager Prognos, Interviewed May 21st 2014

59 Martin Meilchen, Director Product Management Solibro, Interviewed May 28th 2014

60 Stefan Müller, Member of the Board/ Chief Operating Officer, Enerparc, Interviewed May 19th 2014

Technology wise, the majority of the Chinese firms chose the crystalline silicon technology. Reasons for this could be the higher efficiency, that the technology was more established,[61] and/or the availability of standardised production lines. For thin film, especially CIGS and cadmium telluride, no turn-key manufacturing lines were available.[62] Cadmium telluride had so far been the only thin film technology successfully mass-produced. The process development for cadmium telluride has been driven by First Solar, who develops processes in-house (MIT OpenCourseWare, 2014b). For CIGS, there were still many obstacles regarding the process development, and it was not yet possible to manufacture modules on a large scale.[63] Regardless of why the crystalline silicon technology was adopted in China, it had large effects on the future outcome for the different PV technologies. With a dominant design, firms commonly dare to invest in high volume production and prices fall as an effect. The mass production of crystalline silicon modules increased entry barriers through economies of scale, making it more difficult for the thin film technologies to catch up.

The development of the Chinese PV industry was driven by European policy-driven demand. Since 2002, over 95 per cent of the Chinese module production has been exported (Stone and Associates, 2011). The Chinese firms' large capacity increases and the subsequent price drops of modules came as a surprise for many German manufacturers, who underestimated the ability of the Chinese firms' to produce high quality PV cells and modules.[64] Of the top 15 PV producers in 2010, 12 had no manufacturing in Europe (Bajenescu, 2013). The Chinese expansion ended in a massive oversupply, pushing the prices lower and lower, which was one of the main reasons for the years of consolidation that were to follow.[65]

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[61] Thomas Grigoleit, Director Energy, Environment, and Resources German Trade and Invest, Interviewed May 22nd 2014

[62] Rutger Schlatmann, Director PVcomB, Interviewed May 23rd 2014

[63] Rutger Schlatmann, Director PVcomB, Interviewed May 23rd 2014

[64] Stefan Gall, Senior Scientist Helmholtz-Zentrum Berlin, Interviewed May 23rd 2014

[65] Stefan Nitzsche, Sales/Marketing Director Solarion, Interviewed May 26th 2014

6.4 Industry consolidation

Many events combined led to a large industry consolidation in the early 2010's. The overcapacity and the subsequent module price decreases combined with reduced subsidies for PV, the financial crisis in 2008, and the European debt crisis from 2009 onwards led to an industry wide crisis with reorganizations, mergers, acquisitions, and bankruptcies (Sun et al, 2014). The first year Q-Cells ever made a loss was 2009. They had to cut 20 per cent of the workforce and move production from Germany to Malaysia in order to lower the production costs. Suntech had to reduce production at the same time, and cut the workforce by 10 per cent (Johnstone, 2011). Due to overcapacity, prices plummeted, which kept the demand up but severely pressured margins throughout the PV value chain (Aanesen, Heck, and Pinner, 2012). The module prices of 2009 were up to 40 per cent lower than those during 2008 (Johnstone, 2011).

The year of 2012 became a very challenging year for the entire PV industry. During 2011 and 2012, subsidies for PV were cut in several European nations, including Italy, Spain, France, and the Czech Republic (China Greentech Initiative, 2011). For the first time since the industry growth took off, it experienced a no-growth year. The European market decreased, which was compensated for by growing markets such as China, Japan, India, and the US. The price competition among module suppliers intensified, especially smaller producers in Europe and the US were hit hard, and many went into insolvency proceedings (IEA, 2013). Despite declining module prices, the financial and debt crisis in 2008 and 2009 affected the financial situation of downstream actors badly (Cassell, 2014). The decrease of PV installations in Europe and with PV manufacturing firms integrating downstream, competition in the downstream value chain intensified. This resulted in consolidation, although not as severe as among cell and module manufacturers.[66] As oversupply and price competition tend to characterize a mature industry, this is one indication that the industry was leaving the growth stage and entering the maturity stage of the industry life cycle. A further indicator is the subsequent high exit rates in the PV industry, as a 'shake-out' commonly occurs during industry maturity. Q-Cells, just a few years ago the biggest cell manufacturer in the world, filed for

[66] Oliver Lyncker, Director Marketing and Business Development Phoenix Solar, Interviewed June 2nd 2014

bankruptcy in 2012.[67] As many other European firms, Q-Cells was purchased by an Asian firm, in this case by South Korean Hanwha SolarOne. However, as we will see later on, several factors suggest that the PV industry has barely entered the growth stage. The consolidation of the recent years may therefore have been a small 'shake-out' in a early growth stage.

The crisis hit PV firms globally, but it hit the European firms harder than the Chinese. Many smaller Chinese manufacturers went bankrupt during this time, but the bigger ones were able to survive (Sun et al, 2014). A main reason why large Chinese firms fared better was that they had advantages connected to economies of scale.[68][69] Increasing importance of scale is common in industries in the mature stage of the industry life cycle, and so there are several signs that the PV industry was moving towards maturity at this time. Scale gives a lower cost structure, which became increasingly important with the large price drops. Moreover, there are structural disadvantages related to manufacturing in Europe, as most costs of manufacturing are higher.[70] Another reason for the higher survival rate among large Chinese firms was that they were backed up by the Chinese government, enabling the capital requirements for necessary investments (Enkhardt, 2013).[71] Moreover, when the polysilicon price was high during the polysilicon shortage, many German PV firms benefited from long-term contracts with polysilicon producers. However, when the overcapacity of polysilicon hit, the spot market price became lower than the contract prices.[72] What had been a cost advantage for the German firms, became a big liability. They were now forced to purchase raw material to a substantially higher price through the supply contracts than many Chinese firms had to pay on the spot market.

To make matters worse for the European and US producers, a PV module was becoming more of a commodity. Hence, the Chinese firms' cost advantages became

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67 Martin Meilchen, Director Product Management Solibro, Interviewed May 28th 2014

68 Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

69 Gerhard Willeke, Coordinator PV Fraunhofer ISE, Interviewed June 3rd 2014

70 Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

71 Rutger Schlatmann, Director PVcomB, Interviewed May 23rd 2014

72 Gerhard Willeke, Coordinator PV Fraunhofer ISE, Interviewed June 3rd 2014

an even more important factor than it had been before. Several interviewees, among them Frank Peter, Deepak Kumar, Stefan Müller, and Adrian Honey, state that most modules have good quality and that it is increasingly hard, if not impossible, to differentiate on product offering. This commoditization of the product is yet another sign of industry maturity. As commoditization moreover is a common effect of the emergence of a dominant design, this further speaks in favour of crystalline silicon as a dominant design. Some, however, claim that product differentiation still is possible through the use of thin film, which can be used in some applications where crystalline silicon modules cannot.[73]

"A module is a module is a module." [74]

The rush of firms to the PV industry has been called a gold rush,[75] and it is often noted that in the actual gold rush in Klondike, US, the most profitable were those supplying miners with spades (Morse, 2003). The equivalent in the PV industry could be equipment manufacturers. They too had a few tough years during the PV industry consolidation,[76] but they did not face as severe times as the cell and module manufacturers.[77] Moreover, the Chinese firms have step by step entered the production in several parts of the PV value chain and now cover most segments domestically. One thing that still mainly is imported from Europe and the US is production equipment (China Greentech Initiative, 2011).[78] This shows that production in China does not necessarily have to be the end of the industry's economic benefits in Europe.[79] However, Chinese firms have been entering the equipment manufacturing segment to support domestic PV manufacturers (Sun et al, 2014).

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[73] Stefan Nitzsche, Sales/Marketing Director Solarion, Interviewed May 26th 2014

[74] Stefan Müller, Member of the Board/ Chief Operating Officer, Enerparc, Interviewed May 19th 2014

[75] Stefan Müller, Member of the Board/ Chief Operating Officer, Enerparc, Interviewed May 19th 2014

[76] Bernd Rau, Senior Vice President Roth & Rau, Interviewed May 27th 2014

[77] Thomas Grigoleit, Director Energy, Environment, and Resources German Trade and Invest, Interviewed May 22nd 2014

[78] Eckhart K. Goura, Magazine Editor, Chinese Edition pv magazine, Interviewed at Intersolar June 5th 2014

[79] Frank Peter, Senior Project Manager Prognos, Interviewed May 21st 2014

To summarize, the years of consolidation have been a cold shower for many firms in the PV industry, who had become used to double digits growth (Johnstone, 2011). EPIA (2014a) describes how an industry characterized by oversupply at some point has to come to a greater balance between supply and demand. In the past decade, most demand has been policy-driven and hence highly volatile (EPIA, 2014a). Aanesen, Heck, and Pinner (2012) call the consolidation with its many bankruptcies a 'growing pain' and a sign that the industry is moving towards maturity. The industry might be moving into a phase of more stability,[80] and while the heavy price drops was detrimental to many firms, it has been good for PV as a source of electricity in competition with other energy sources (Johnstone, 2011).

6.5 Emergence and growth of the Chinese market

In 2007, China replaced Germany and became the largest cell-producing nation in the world (IEA, 2008). However, the domestic installation of PV modules was still low and what was produced in China was almost exclusively exported (Vinnova, 2009). When the demand from the European PV market was stalling in 2008 and Chinese PV manufacturers had to scale back production and lay off workers, the Chinese government introduced several national PV incentives aimed at creating a domestic demand. This would help support the growth of the Chinese PV industry (Business Wire, 2010). Moreover, China is facing a rapidly growing domestic energy demand and increasingly severe environmental problems, resulting in an urgent need for change in the domestic energy mix, which also contributed to the governmental decision of supporting a domestic PV market (Sun et al, 2014).

Historically, the cost of PV electricity has been too high to be competitive on the Chinese energy market. Of the few early installations, a large majority was off-grid installations in remote areas. In 2009, the Chinese government initiated two subsidy programs for PV. The 'Large-scale PV power station concession bidding' supported on-grid power plants whereas the ''Golden-sun pilot project' supported on-grid residential systems and off-grid applications in remote areas. As a result, the cost of PV generated electricity decreased significantly (Zhang and He, 2013). The economic incentives evolving from these two programs became, according to Sun et al (2014), the most important drivers for the development of the Chinese PV market.

[80] Anonymous, Sales Director Suntech, Interviewed at Intersolar June 4th 2014

On-grid power plants became the dominant PV application in China during 2008, and have been ever since (EPIA, 2014a). From 2010, the Chinese market accelerated and most installations were on-grid power plants in the northwest of China (Sun et al, 2014). From 2010 to 2012, the cumulative PV capacity increased nearly nine fold and reached 7 gigawatts. In 2013 alone, an additional 11.3 gigawatts were installed, accounting for 30 per cent of the total global installations (Roney, 2014), see Figure 6.8. The impressive growth of the Chinese PV market is expected to continue, yet only a few years ago the Chinese market was not large enough to be discussed at a global industry level.

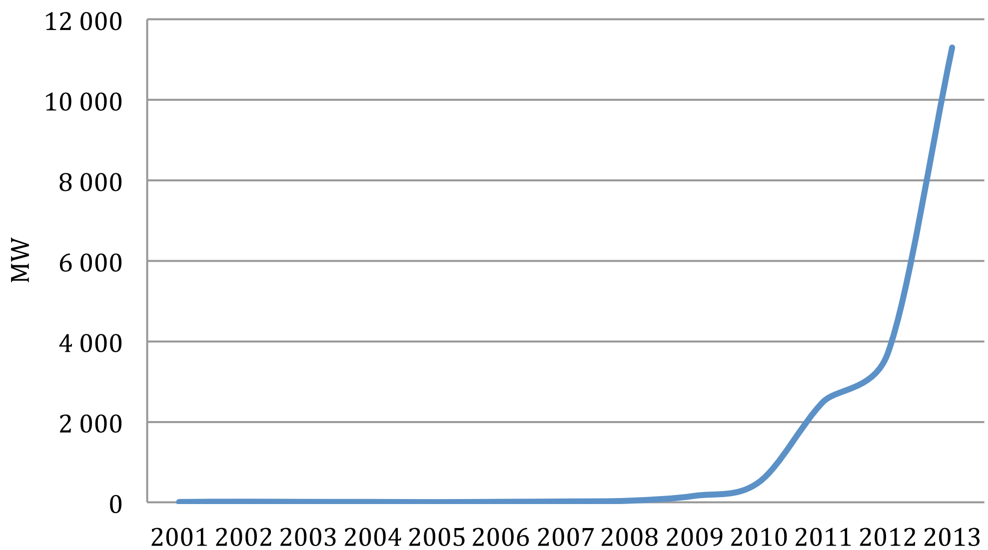

Figure 6.8: The annual PV instalments in China, 2001-2013. Source: Roney (2014)

Most PV power plants in China are located in developing regions and long-distance transmission is required to make use of the PV electricity. The Chinese government has in recent years increased the initiatives for smaller local PV systems that do not require long-distance transmission (Roney, 2014). In 2011, the first national feed-in tariffs were introduced (Zhang and He, 2013), and the government is aiming to reach over 8 gigawatts accumulated installed rooftop capacity during 2014 (Roney, 2014). Even though the residential segment is growing, power plants will most likely continue to be the dominant application for PV in China the upcoming years.[81] The overall Chinese market is expected to continue to grow. The Chinese

[81] Eckhart K. Goura, Magazine Editor, Chinese Edition pv magazine, Interviewed at Intersolar June 5th 2014

government has announced a goal of 70 gigawatts installed capacity by 2017, and to reach that target many installations are yet to come (Roney, 2014).

6.6 Increasing protectionism

The years of consolidation were tough on the PV industry. During 2012, which is often described as the worst year thus far, more than half of all PV firms filed for bankruptcy or were acquired by other firms (Renewable Energy Focus, 2013). In some countries, the PV industry had become an important part of local economies, providing jobs and other benefits. The many bankruptcies led to job losses, and some firms and local governments were looking for a quick solution to stop this from happening. This is when anti-dumping and anti-subsidy duties became a reality for the PV industry (IEA, 2013).

The first country to impose anti-dumping and anti-subsidy duties was the US, who in 2012 imposed duties on PV modules made with Chinese cells. The rationale behind the duties was that Chinese firms was considered to have been dumping prices and gaining advantages through unfair subsidies from their government, leaving US firms unable to remain competitive (IEA, 2013). The EU was next; in 2013 they imposed strong anti-dumping and anti-subsidy duties on PV modules from the Chinese firms which had not been willing to agree to a minimum price (EUbusiness, 2013). There are however those who say that the anti-dumping duties came too late; the damage had already been done and there was no going back (Cardwell and Bradsher, 2013). Adrian Honey agrees, and thinks that the duties have made matters worse, and Stefan Müller argues that the duties have been hurtful for European EPC firms and system integrators.

The US and EU anti-dumping and anti-subsidy duties created new difficulties for Chinese cell and module manufacturers of which many already had struggled throughout the industry consolidation (Sun et al, 2014). A slightly unexpected result of the US and EU protectionism was that it gave Chinese firms further incentives to focus on their domestic market. The Chinese government decided that the Chinese firms needed to become less dependent on markets abroad (Zhang and He, 2013;

Sun et al, 2014), and the Chinese market has really taken off since.[82] Moreover, there is a risk that the US and EU regulations trigger a development where similar protectionist regulations are imposed around the world (Sun et al, 2014). China's response to the US and EU duties was to impose anti-dumping duties on solar-grade polysilicon exported from the US and Korea. Europe, almost exclusively referring to the German polysilicon producer Wacker, was exempt after having reached an agreement just before the duties were set up in July 2013 (Meza and Feng, 2013). There are however small indications that the duties in some cases have had the desired effects. Since the anti-dumping duties were imposed, PV production have increasingly been located in Taiwan, as Chinese firms tried to avoid the US and EU duties by purchasing cells from abroad (IEA, 2013). Therefore, the US is investigating whether cells and modules from Taiwan should be included in the regulations (Heffner and Ferrin, 2014).

[82] Eckhart K. Goura, Magazine Editor, Chinese Edition pv magazine, Interviewed at Intersolar June 5th 2014

7. Current industry structure

The following chapter will describe the current state of the PV industry, focusing mainly on the market development, production, vertical integration and dominant technology.

The last years have been difficult for the PV industry, which has been characterized by overcapacity, price erosion, and significant consolidation among firms. However, the numbers from 2013 show signs of recovery (Mehta, 2014b). During 2013, the global market grew significantly compared to 2012, mainly due to installations in Asia (EPIA, 2014a). This increase in demand eased some of the overcapacity as much of the inventory built during 2012 was sold off (Mehta, 2014b). Over the past three years, module prices have dropped over 50 per cent (Solarbuzz, 2014). Module prices seem to have stabilized during 2013, and some of the well-established PV firms were for the first time in several years able to make a profit (Clover, 2014).

The global PV installations during 2013 added up to 38 gigawatts, a new record and 25 per cent more than in 2012. Installations in Europe continued to decrease and the increase in installations was mainly due to a rapid increase of installations in Asia, mainly in China. Germany, which has been the leading nation in the creation of the European PV market, decreased its installations from 7.6 gigawatts to 3.3 gigawatts, see Figure 6.2 (EPIA, 2014a). Further growth is predicted for the PV market in 2014, and countries like China, Japan, and the US are expected to be the driving forces (Solarbuzz, 2013). The European share of global installations will most likely continue to decrease and strong markets will continue to grow in Asia, while markets in Africa and South America are expected to emerge (EPIA, 2014a; Parkinson, 2013).

The past years of price fluctuations, production bottlenecks, increased competition, and uncertain demand have contributed to an increasingly unstable environment and higher transaction costs for PV firms. This has led to increased vertical integration of manufacturing activities along the PV value chain. In 2013, a majority of the large PV firms had to some degree adapted a strategy of vertical integration. Most commonly, PV firms integrate the production of everything from ingots to modules. The capital intensive production of polysilicon is usually left to firms specialized on only this part of the PV value chain (China Greentech Initiative, 2011). It takes too much capital to be successful in both polysilicon and ingot/wafer production.[83] There are many firms in the more service oriented downstream value chain specializing in one or more of these activities (concluded after studying content listed in Appendix I). It is also, however, common for module manufacturers to offer services in some part of the downstream value chain, to get closer to the end consumer of a PV system and to support the distribution and sales of their own modules (Krulewitz and Mehta, 2011). For some module manufacturers, this has become a large part of their business model. First Solar, for instance, has become one of the largest system integrators in the world (Gifford, 2012). It is not only module manufacturers, however, who have been investing in downstream services. Firms specialized in polysilicon or ingot and wafer production have in some cases started to offer project development services (Krulewitz and Mehta, 2011). If the PV industry stabilizes in the future, increased division of labour would be more likely and hence more firms would potentially specialize on a single part of the value chain.

The production level of 2013 increased only marginally from that of 2012 (Mehta, 2014b). According to Mehta (2014b), the PV manufacturers were cautious toward factory utilization and further capacity expansion. The utilization rate among established firms differed significantly from around 30 per cent to nearly full utilization (Mehta, 2014b). Due to the increase in demand that is expected during 2014, Solarbuzz (2013) predicts that PV manufacturers will increase their module production by 25 per cent compared to 2013. The increase in production will most likely be covered by already existing production capacity without a need of further capacity expansions (Solarbuzz, 2013).

China has been the dominating nation in the production of polysilicon, ingots and wafers, cells and modules for some years now (IEA, 2013). Seven of the top ten PV module producers in 2013 had their primary production units located in China, see Appendix III. Of the modules produced globally the same year, 65 per cent originated from China, see Figure 7.1. Other Asian nations, primarily Japan,

[83] Mathias Bremer, Director Strategic Marketing Wacker, Interviewed May 30th 2014

Malaysia, Taiwan, and South Korea, increased their share of total module production in 2013 and reached 22 per cent of the global production (Mehta, 2014b). Japan's PV installations have increased significantly the past years due to increased governmental incentives, and Japan was the second largest PV market in 2013 (Roney, 2014). As a response to the increase in domestic demand, the Japanese production of PV modules increased by over 20 per cent in 2013. Despite regulations to protect the domestic supply, the module production in Europe and the US continued to decrease and in 2013, their share of global production dropped to 12 per cent (Mehta, 2014b).

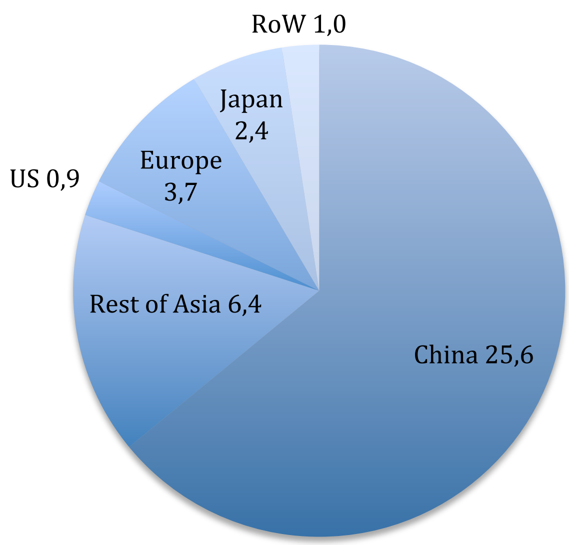

Figure 7.1: Global PV module production share (GW) by region 2013. Source: Mehta (2014b)

Crystalline silicon has for a long time been the main technology on the PV market and in 2013, around 90 per cent of all produced modules were crystalline silicon modules, see Figure 7.2. The production share of thin film further declined to about 10 per cent, which is the lowest production share of thin film since 2006, before the polysilicon shortage in the mid 2000s. According to Mehta (2014b), the continued decline of thin film can be derived from the generally lower efficiency and bankability compared with crystalline silicon technology. It also has to do with the customers' perception of the different technologies. The crystalline silicon technology is deemed more proven, and thin film manufacturers have to deal with questions related to why it would be beneficial to choose a non-dominating technology.[84] This is an example of how a dominant design tends to reinforce itself simply by being dominant. Several thin film technologies are still being developed, but as the crystalline technology is becoming increasingly cost efficient the entry barriers for thin film are increasing.[85] Crystalline modules are developed in largely the same way, towards higher efficiency and thinner wafers leading to less waste. For less established technologies working with much lower volumes, the development efforts are rarely helping each other. For CIGS, for example, firms' development efforts are going in several directions, allowing the crystalline technology to further strengthen its advantage.[86]

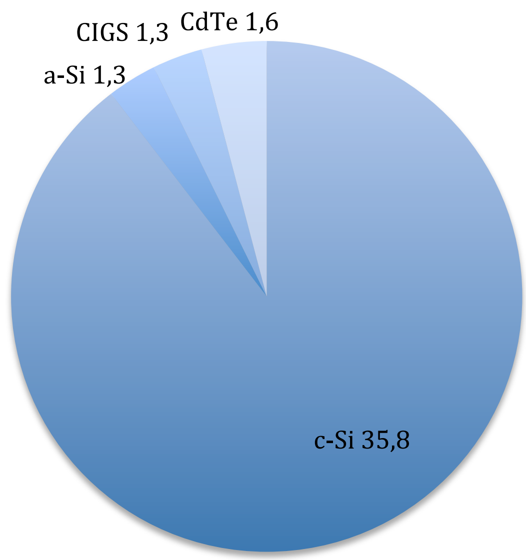

Figure 7.2: Global PV production share (GW) by technology 2013. Source: Mehta (2014b)

Even though the PV industry has shown signs related to the maturity stage of the industry lifecycle, the global PV market is far from saturation. The installations are not replacement purchases, it will take many years before replacement of old systems takes a noticeable share of the market. Even though the industry has grown rapidly the past decade, solar generated electricity covers well below one per cent of

[84] Martin Meilchen, Director Product Management Solibro, Interviewed May 28th 2014

[85] Thomas Grigoleit, Director Energy, Environment, and Resources German Trade and Invest, Interviewed May 22nd 2014

[86] Rutger Schlatmann, Director PVcomB, Interviewed May 23rd 2014

the world's energy consumption. Hence, if PV becomes an important technology in the energy transition the world is likely to see, the growth has merely begun. It is therefore not easy to place the PV industry in the industry life cycle. Even if the industry shows signs of maturity in its overcapacity, price competition and firms exiting, the promise of a massively unexploited market suggests that the industry may be in its very early growth stage.

8. The potential role of Northern Europe

The chapter will explain why manufacturing of crystalline silicon cells and modules is no good bet for Northern European nations. Moreover, three areas of potential interest of these nations are identified and discussed; building strong research competencies within PV to remain in the forefront of technology development, development and manufacturing of equipment, and finally the downstream value chain.

Chinese firms dominate the production of the entire value chain of PV crystalline silicon modules, from polysilicon production to module assembly. Most interviewees are firm in their opinion that manufacturing of crystalline silicon modules is likely to remain in China in the foreseeable future. Cost is and will remain a key factor. With manufacturing in Europe, where the costs are generally higher, firms will have difficulties to compete on the global market.[87] For cells and modules, all European manufacturers that remain successful have moved all or most of their production to low-cost/high-tech countries in Asia.[88] Examples include Norwegian REC, which closed production in Europe and opened a large vertically integrated production facility in Singapore.[89]

As discussed in previous chapters, modules have become a commodity and can be made in China with high quality and low cost. Wheeler and Mody's (1992) view that locational advantages tend to strengthen themselves, further supports that all production steps in the PV value chain will remain in China. China has reinforced its position in the PV industry through developing capabilities in production and lately also in R&D. According to Jacobides and Winter (2005), such capability development determines future capability development. Hence, the fact that the Chinese firms are dominant enhances the chance of them being dominant in the future. The move from Germany to China somewhat undermines this argument. Dominance does not guarantee future dominance but increases the likelihood of it. China's current dominance in terms of share of global production is larger than Germany's dominance ever was, which further strengthens China's position as the future

[87] Anil Vijayendran, Senior Director, Product Management MiaSolé, Interviewed at Intersolar June 4th 2014

[88] Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

[89] Anonymous, Marketing Manager REC, Interviewed at Intersolar June 5th 2014

dominating PV producing nation. The creation of the Chinese PV market, which is now the largest and one of the fastest growing in the world, also speaks in favour of continuing Chinese dominance in crystalline silicon PV manufacturing. Northern European nations have higher cost structures, smaller markets, and face entry barriers mainly in the economies of scale of the already established firms. Hence, investments in production in the value chain of the crystalline silicon technology in any Northern European country are unlikely to pay off.

If the PV industry is in its very early growth stage, many new firms will enter the industry. If Northern European countries would take a part of the production in the PV value chain, firms in these nations would most likely have to produce premium products at a premium price. This premium, however, would have a limit.[90] China is investing in R&D to improve the crystalline cell efficiency, which makes it difficult for others to develop a premium product at reasonable cost. Northern European countries may therefore have a better chance if they were to invest in other PV technologies. Such a technology could be a thin film technology, or another emerging PV technology. A strategy could be to aim for niche applications where crystalline silicon modules cannot easily be used. If the PV market expands, the market for such niche applications would grow, even if it would remain a small share of the global PV market. What it all comes down to, however, is usually the cost per watt. Investing in a more expensive technology, and one that is not the dominant, is a risk that has to be assessed. There is also the risk that what happened in crystalline silicon would happen to newly developed technologies as well; that Chinese firms would enter and dominate this technology too.[91, 92]

An area where Northern European countries could direct their efforts is R&D. By focusing on new techniques close to the forefront of technology, Northern European countries could supply the industry with the latest solutions from product and process innovation.[93] Several interviewees mention innovation as a way western

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90 Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

91 Stefan Gall, Senior Scientist Helmholtz-Zentrum Berlin, Interviewed May 23rd 2014

92 Frank Peter, Senior Project Manager Prognos, Interviewed May 21st 2014

93 Thomas Grigoleit, Director Energy, Environment, and Resources German Trade and Invest, Interviewed May 22nd 2014

nations can contribute in the PV value chain. One opportunity could be to have small production lines closely connected to research centres, where new technologies and equipment could be tested.[94] These technologies could be patented and either sold or commercialized through licensing agreements with global manufacturers. However, to make a strategy work that focus on R&D and innovation, continuous research is vital. There are difficulties related to this opportunity, but if anything is certain it is that the PV technology will only improve,[95] and that the efficiency of the Chinese modules will increase with time.[96] What is not certain, however, is where this technology will originate from. The question is if it is likely to see research and technology development in Europe if the production remains in China.

Manufacturing equipment is an area in which the Chinese PV industry still relies on imports from Europe and the US.[97] Among others, Gerhard Willecke and Stefan Gall mention equipment manufacturing as a way for European countries to participate in the PV industry. Even though the interviewees have a largely German perspective and fact that Germany already is a well-established equipment manufacturer, other Northern European countries may have a window of opportunity here. If PV becomes a power source of magnitude in the future, significantly higher volumes will have to be produced, and for this, manufacturing equipment would be needed. The equipment is not commodity products, and the development and manufacturing is complex.[98] China has, however, explicitly stated that they do want to produce equipment domestically as well.[99]

A part of the PV value chain where economies of scale is less important, and where the final product is not a commodity provides Northern Europe a better position to inhabit successful firms. In the downstream PV value chain, both these conditions hold true. Even though the PV module has become a commodity, the PV system has

94 Frank Peter, Senior Project Manager Prognos, Interviewed May 21st 2014

95 Deepak Kumar, Senior Consultant Apricum Group, Interviewed May 22nd 2014

96 Gerhard Willeke, Coordinator PV Fraunhofer ISE, Interviewed June 3rd 2014

97 Eckhart K. Goura, Magazine Editor, Chinese Edition pv magazine, Interviewed at Intersolar June 5th 2014

98 Frank Peter, Senior Project Manager Prognos, Interviewed May 21st 2014

99 Rutger Schlatmann, Director PVcomB, Interviewed May 23rd 2014

not,[100, 101] making it possible to compete on other factors than price. The lower importance of economies of scale also makes it easier for small firms to compete. This in combination with the fact that downstream actors benefit from being close to the end customers makes it more likely for downstream activities to be supplied by local firms. Martin Meilchen at Solibro believes that if the final customer is in Europe, so will the last steps of the PV value chain.

[100] Adrian Honey, Head of Marketing Lorentz, Interviewed May 20th 2014

[101] Stefan Müller, Member of the Board/ Chief Operating Officer, Enerparc, Interviewed May 19th 2014

9. Discussion

This brief chapter comments on the study's use of methodology, evaluates the credibility of the results, and finally suggests areas for further research.

The nature of the study required a large focus on qualitative data and hence also qualitative research methods. The interviews conducted have significantly contributed to the results, and it would have been difficult to collect much of the interview data elsewhere. While interviewing is a time consuming data collection method, the information accessed through interviews and the triangulation of data they allow motivate the choice of research method.

As described in the methodology chapter, the credibility of a case study is increased by the use of triangulation, thick case descriptions, and by looking at potential biases. Most of the data has been triangulated and the use of one-source data is very limited. The interviews, the visit to Intersolar Europe, and the document readings resulted in a large amount of data: much of which did not make it into the report. Hence, the case description is considered thick enough. The perhaps most interesting to discuss when it comes to credibility is potential biases. The interviewees all have a certain amount of bias depending on experience and field of work within the PV industry. The effects of biases may have been increased by the fact that most interviewees are German and hence provided a German perspective. Some have however long experiences from working abroad, and at Intersolar Europe the focus was to gain insights and perspectives from China and the US. The focus on Germany is further justified as a large part of the PV industry development took place there.

Some information has been difficult to obtain, for instance data on the historical development of ingot and wafer production. The results may have been broader in terms of value chain scope, if such data had been more readily available. Furthermore, capabilities of Northern European countries were due to time constraints not included in the scope. However, it is important to note that if these capabilities had been researched and taken into consideration, the answer to RQ3 might have been slightly different. This could be a topic for future research and investigation.

The PV module has been the focal point of the study, and the steps of the value chain included in the scope are all directly connected to the module. Other PV system components have not been investigated in this study. Such an investigation would likely broaden the understanding of the dynamics of the PV industry. Especially interesting for further research could be the potential of storage solutions. Of all the system components, including the PV module, several interviewees believe that the storage solutions will experience the largest technology progress and cost decrease in the near future. This could have important effects for solar as an energy source, as it would reduce the importance of solar's big disadvantage; that it only works at daytime.

10. Conclusions

This chapter summarises the findings by presenting a brief answer to each research question and hence fulfils the purpose of the thesis.

RQ1: How has the PV industry developed during the past 15 years?

Japan was the dominating PV manufacturing nation when Germany started to support the PV technology in the early 2000's. The increase of the German feed-in tariff in 2004 gave the German PV market a massive boost. Demand spurred, and domestic production soon followed. Within a few years, Germany was the main PV producer in the world. The demand exceeded supply, and the resulting high profits and easy-to-access market made the industry attractive to enter. Eventually, the large demand and resulting need for polysilicon led to a polysilicon shortage. Polysilicon prices increased and the shortage lasted between 2005 and 2008. During the shortage, firms tried to secure their polysilicon supply by signing long-term contracts with polysilicon suppliers, giving them the security they needed to make the necessary investments. The firms that failed to sign long-term contracts were in the worst case left unable to produce. After a massive capacity increase, however, the polysilicon price dropped and many of the newly established polysilicon producers who entered to profit from high polysilicon prices went bankrupt.

While the German market and industry grew, the Chinese government invested in PV firms and created policies with the intention to create a Chinese PV industry. Chinese firms began PV production on a large scale with cells and modules, eventually covering all steps of the PV value chain. Essentially all Chinese modules were exported, mainly to Europe and in particular supplying the policy-created German market. Chinese firms successfully lowered the costs of production, much due to the large effects from economies of scale but also due to China's generally low cost structures. Moreover, use of mainly German production equipment enabled the rapid scaling of manufacturing capacity. The large investments in the crystalline silicon technology made it increasingly difficult for the thin film technology, which lost most of its cost advantages. Eventually, the Chinese expansion left the industry with a large oversupply.

In 2009, the demand of PV modules was negatively affected by the financial crisis, leading to less investments and cutbacks in PV policies in several nations. This enhanced the problem of oversupply, and module prices dropped, leaving PV firms struggling with low margins. This led to a shake-out of firms, during which many firms filed for bankruptcy, were acquired, or merged. The year of 2012 was the first no-growth year in the 21th century and even large firms filed for insolvency. The large Chinese firms also struggled, but they survived to a higher degree than other firms, much due to economies of scale, backing from the Chinese government and low cost structures. The Chinese firms were further able to supply a rapidly growing domestic market. China had previously exported almost all production. In 2010, however, two big policy programs were initiated to increase domestic demand, and installations started to grow quickly. China became the largest market in the world in 2013.

A recent development in the PV industry is the protectionism several countries have used in an effort to protect their local PV industries. It started with the US imposing anti-dumping and anti-subsidy duties on Chinese modules in 2012. The EU followed in 2013, whereafter China answered by imposing duties on US and South Korean polysilicon.

RQ2: What characterises the PV industry of today?

China is since 2013 the largest PV market in the world. The global market is growing; mainly due to high installation rates in Asia as the European market growth has stagnated. Which segment that dominates varies greatly between markets. The majority of Chinese installations, for instance, have been for power plants, whereas rooftop installations are the most common type in Germany. Governmental programs and policies have been, and still are, key for the continuing market development. The main PV technology, with around 90 per cent market share, is the crystalline silicon technology. The production of all steps of the value chain, from polysilicon to modules, is centred in China and most large firms are vertically integrated from ingots to modules. Other important manufacturing nations include the US, Malaysia, Taiwan, Japan, South Korea, and Germany. The crystalline technology is, at least for now, a dominant design and the large manufacturing firms enjoy benefits connected to economies of scale. The industry is overall characterized by oversupply, which creates intense competition between the firms in the industry and there are hence large incentives to cut costs and increase module efficiency. It is difficult to place the PV industry in a stage of the industry life cycle. Whereas price competition, oversupply, and industry consolidation points to maturity, the small share of solar in the world's energy consumption shows great growth potential, making it likely that we are only seeing the beginning of the growth stage.

RQ3: In which parts of the PV industry is it likely that firms from Northern Europe can compete successfully?

In the value chain of crystalline silicon modules, the steps between polysilicon and modules are largely dominated by Chinese firms, and are expected to remain so. The Chinese firms have lower costs, the module itself is in many ways a commodity, and the Chinese has a large, still growing, domestic market to supply. This all speaks in favour of continuing Chinese dominance. Therefore, firms in Northern Europe are not considered likely to succeed if they were to enter. An area that may be beneficial for Northern European firms to engage in is forefront product and process R&D. If technologies, superior to the existing or suitable for niche applications, were to be developed, these could be charged with a premium price and hence price competition would be less important. This, however, requires continuous improvements of the technology at hand, as an innovation eventually spreads to the low-cost/high-tech countries as well. Another opportunity could be to develop and produce manufacturing equipment, which is already an established industry in countries such as Germany. Even if PV would represents only five per cent of the global energy supply in the future, large amounts of production equipment will be required to produce the volumes needed. The development of such machinery is rather complex, making it suitable for western nations. A final opportunity would be in a non-commodity business, where economies of scale is of less importance, making downstream activities an interesting part of the PV value chain for Northern European nations. As downstream firms tend to have advantages of being local, this could be an opportunity in countries with a domestic PV market.

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Appendices

Appendix I, Annual reports and webpages

Annual reports

Anwell Technologies, 2012

Boeing, 2013

Canadian Solar, 2013

Centrosolar Group, 2012

Coring, 2012

Emcore, 2013

Entech Solar, 2011

First Solar, 2013

GCL-Poly Energy Holding, 2013

Gintech Energy Corporation, 2013

JA Solar Holdings, 2012

Kaneka Corporation, 2013

LDK Solar, 2012

OCI, 2012

Phoenix Solar, 2013

PowerFilm Solar, 2013

PV Crystalox Solar, 2013

REC Silicon, 2013

Rexel, 2013,

Sharp, 2013

Soitec, 2011-2012

SolarCity, 2012

SunEdison, 2013

SunPower, 2013

Suntech Power Holding, 2011

Trina Solar, 2012

Wacker, 2013

Yingli Green Energy Holding, 2012

Webpages

Company	Webpage
Activ Solar	www.activsolar.com
AEE Solar	www.aeesolar.com
BayWa r.e. Solar Systems	www.baywa-re-solarsystems.com
Belectric	www.belectric.com
Enerparc	www.enerparc.de
Juwi	www.juwi.com
Krannich Solar	www.krannich-solar.com
Metgen	www.metgen.com
Nusolar Energ	www.nusolar.com
Parabel	www.parabel-solar.com
RCS Solar	www.rcssolar.com
Solar Electric Supply	www.solarelectricsupply.com
Solar Energy Australia	www.solaraustralia.com
Solarvis Energy	www.solarvisenergy.com
Soligent	www.soligent.net
SunFields Europe	www.sfe-solar.com
Twin Solar USA	www.twinsolarusa.com
Wholesale Solar	www.wholesalesolar.com

Please note that many more websites have been browsed throughout the study process. These however represent those of firms, mainly in the downstream value chain, which did not have available annual reports.

Appendix II, Interviewees

Interviews

Name	Organisation	Title	Date	Interview mode
Lars Stolt	Solibro	Chief Technology Officer	May 8	Telephone
Mirko Held	Centrosolar	Head of Product Management	May 19	In person
Stefan Müller	Enerparc	Member of the Board/ Chief Operating Officer	May 19	In person
Adrian Honey	Lorentz	Head of Marketing	May 20	In person
Frank Peter	Prognos	Senior Project Manager	May 21	In person
Deepak Kumar	Apricum Group	Senior Consultant	May 22	In person
Thomas Grigoleit	German Trade and Invest	Director Energy, Environment, and Resources	May 22	In person
Rutger Schlatmann	PVcomB	Director	May 23	In person
Stefan Gall	Helmholtz-Zentrum Berlin	Senior Scientist	May 23	In person
Stefan Nitzsche	Solarion	Sales/Marketing Director	May 26	In person
Marco Burkhardt	PV Crystalox	Managing Director	May 27	Telephone
Bernd Rau	Roth & Rau	Senior Vice President	May 27	In person
Martin Meilchen	Solibro	Director Product Management	May 28	In person
Mathias Bremer	Wacker	Director Strategic Marketing	May 30	In person
Oliver Lyncker	Phoenix Solar	Director Marketing and Business Development	June 2	In person
Gerhard Willeke	Fraunhofer ISE	Coordinator PV	June 3	In person
Robert Küster	RWE	Group Strategy and Corporate Development	June 12	Telephone

Personal communication at Intersolar Europe, June 4-5

Name	Organisation	Title
Marguerite Durant	PV Cycle	Communications Coordinator Europe
Cornelia H. Jahnel	Heliatek	Marketing
Nathaniel Lee	Hyundai	Sales Manager, Europe & Africa
Anil Vijayendran	MiaSolé	Senior Director, Product Management
Anonymous	Suntech	Sales Director
Alistair Mounsey	JA Solar	UK Country Manager
Nick Strevel	First Solar	Manager – Technical Saler
Curtis Ash	Innotech Solar	International Sales Manager
Eckhart K. Gouras	pv magazine	Magazine Editor, Chinese Edition
Karsten Bender	Calyxo	Head of Sales
Bill O'Connor	Solar Industry Magazine	Account Executive
Anonymous	REC	Marketing Manager

Appendix III, Top PV manufacturing firms

Polysilicon

Top four solar-grade polysilicon producers 2012

	Company name	**Country**
1	GCL	China
2	Wacker	Germany
3	Hemlock	USA
4	OCI	South Korea

Source: Ali-Oettinger, 2012

Cell

Top 10 Cell suppliers by in-house procuction volumes 2013

	Company name	**Country**
1	Yingli Solar	China
2	JA Solar	China
3	Trina Solar	China
4	Neo Solar Power	Taiwan
5	First Solar	USA
6	Motech	Taiwan
7	Jinko Solar	China
8	Gintech	Taiwan
9	Canadian Solar	Cannada
10	Hareon Solar Technology	China

Source: Colville, 2014

Module

Top to module suppliers by production volume 2013

	Company name	**Country**
1	Yingli Solar	China
2	Trina Solar	China
3	Canadian Solar	Cannada
4	First Solar	USA
5	JA Solar	China
6	Jinko Solar	China
7	Kyocera	Japan
8	Flextronix	Singapore
9	Solar Frontier	Japan
10	Sharp Solar	Japan

Source: Mehta, 2014