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Utilising Upgrading Mechanisms for Survival

- *The case of the German solar module manufacturing industry*

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Abstract

This research paper investigates the recent photovoltaic industry crisis in Germany. For the case study 9 leading German solar module manufacturing companies, 1 silicon manufacturer and 3 industry experts, working at the top research institutes, were interviewed through semi-structured interviews. In order to contribute to research, this study's first aim is to investigate the upgrading processes which helped solar module manufacturers in Germany to survive the crisis, while a second aim is to contribute to the research of knowledge base upgrading, further conceptualising van Tuijl et al.'s (2016) early framework, by investigating how firms' upgrading mechanisms relate to the types of upgrading and knowledge bases. The study contributes to the upgrading mechanism framework, by extending it and demonstrating the value of using two additional mechanisms: internal and acquiring to the main framework of mobility, monitoring and collaborations. The findings from the research suggest that *Collaborations, Monitoring* and *Internal* mechanisms were the most important for the survival of the price-uncompetitive German PV firms, while *Mobility* and *Acquiring* were seen as less important. Furthermore, in the first study of its kind, it shows the linkages that exist between upgrading mechanisms, knowledge bases and the types of upgrading.

Key Words: *Upgrading, Upgrading Mechanisms, Knowledge Bases, Dominant Design, Survival*

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Abbreviations

BIPV - Building Integrated Photovoltaics

CEO - Chief Executive Officer

CIGS - Copper Indium Gallium Selenide, a thin-film technology

EPC - Engineering, Procurement and Construction

FAB - Fully integrated turnkey production line

GW - Gigawatt

IB - International Business

IP - Intellectual Property

OEM - Original Equipment Manufacturer

PV - Photovoltaics

R&D - Research and Development

TPO - Thermoplastic Olefin

1. Introduction

1.1 Background

The chapter introduces a background to the topic of the paper, focusing on the recent crisis in the German solar module manufacturing sector and the theoretical field of upgrading. This is followed by a problem discussion, which ends in the purpose of the paper and the research questions. The chapter is concluded by the delimitations of the research.

The environmental problems that the world is facing today are one of the most important issues that has to be solved. Countries around the globe are trying to build a low carbon future by embracing renewable energy developments. The solar industry is the fastest growing industry from all branches of renewable energies like wind, hydropower, biomass, geothermal and other. Significant reduction in solar module prices and manufacturing costs has led to rapid growth in the industry. The production of solar power has increased 60-fold in the last 10 years, while the production capacity has doubled every 20 months (Shankleman, 2016). Germany started as the leader in the industry, however, today half of the solar power installed per year is in China, while the whole Asia made up two thirds of new installed capacity in 2016 (Solar Power Europe, 2016). The demand for solar energy has moved together with the lower manufacturing costs to Asia. The German solar industry was left out in the midst of the crisis in 2011-2012 with an oversupply of lower priced solar modules from Asia, decreased local demand and lower subsidies from the German Government. The majority of German PV (Photovoltaics) module producers went bankrupt, because they were not capable to survive price competition with Chinese manufacturing companies (ProSun, 2017), even though the industry had received large support from the German Government (Wackerbauer & Lippelt, 2012). In total 27 PV module producers went insolvent in Europe, among them Q-Cells, one of the largest module manufacturers worldwide. Today, Chinese products account for 80% of total PV goods sold within EU, while European manufacturers are only holding a 13% of domestic market share. At the time when German companies were going insolvent, Chinese manufacturers were increasing production capacities (ProSun, 2017).

Through globalisation a larger number of firms worldwide have the possibility to engage in international trade, however, it has also increased the competition in markets (Kaplinsky & Readman, 2001). Manufacturing enterprises in developed countries are facing increasing competition from the international market and have to develop their skills of activities or move to market niches, which are protected by entry barriers and isolated from the international pressure (Humphrey & Schmitz, 2002). To innovate thus becomes important for the survival of firms (Kaplinsky & Readman, 2001). An emerging and important subject in this field of innovation is *upgrading.* In International Business (IB) literature, upgrading is viewed through the competitiveness approach, where firms, clusters or entire nations may use upgrading to improve their competitive position (e.g. Porter, 1990). In the context of innovation, upgrading means "innovating to increase value added" (Giuliani, Pietrobelli & Rabellotti 2005, 522) and literature stresses the importance of upgrading as an influencing factor for firms' performance (Humphrey & Schmitz, 2002). The value chain framework discusses four types of upgrading: product, process, functional (functions in the value chain) and chain upgrading (moving to a new value chain) (Kaplinsky & Readman, 2001). Upgrading does not only relate to breakthrough innovations, but also to incremental innovations and innovations which are new to the firm, while not necessarily new to the market (Giuliani et al., 2005).

How the process of upgrading takes place can be understood by using the concept of knowledge bases (van Tuijl et al., 2016). Knowledge base literature differentiates between analytical, synthetic and symbolic knowledge, which represents different types of knowledge that powers innovation processes (Grillitsch, Martin & Srholec, 2016). Different research fields have argued that certain knowledge bases are the most important for firms' innovation, while the knowledge base literature views all three forms of knowledge bases as innovation sources and none should be determined a priori as more important (Asheim, Boschma & Cooke, 2011). The combining of knowledge bases have been indicated as an important factor for company's performance in recent studies, however, which types of knowledge bases and combinations of knowledge bases are beneficial for innovation is a widely unexplored area (Grillitsch et al., 2016; Martin & Moodysson, 2011). A recent study has looked at how different knowledge bases can be linked to upgrading mechanisms. Upgrading mechanisms is a new concept that looks at what mechanisms facilitate upgrading (van Tuijl et al., 2016). Mobility, monitoring and collaborations have been used in previous studies in the field (e.g.

Martin & Moodysson, 2011) in combination with e.g. learning by doing (van Tuijl et al. 2016).

1.2 Problem discussion

The PV industry is not the first industry to have a shakeout of competitors in modern times. Several other industries, such as, automobiles, penicillin, tires and televisions have suffered the same faith (Klepper, 2002). According to theory, shakeouts usually occur in the phase where a dominant design surfaces and competition moves to price-competition where low cost production and economies of scale becomes two of the most important competitive advantages (Argyres & Bigelow, 2007).

Several previous studies have researched factors, which influence firms' chances to survive in these shakeouts. Size and age, from a firm level perspective, have traditionally been seen as factors which has a positive relationship to the probability of survival for firms (Evans, 1987; Hall, 1987; Dunne, Roberts & Samuelson, 1989). From an industry level perspective, demand factors, such as technology characteristics, (Audretsch, 1991; Malerba & Orsenigo, 1999) the product life cycle (Suarez & Utterback, 1995; Agarwal and Gort, 1996) and market growth and size (Mata & Portugal, 1994) have shown to be of importance for the survival of firms. While these studies focus on structural components of firms or the external environment, only a few studies have researched the probability to survive by investigating the role of innovation inside the companies themselves (Cefis & Marsili, 2006).

Since German module manufacturers cannot compete on price in the market (see Appendix 11.1 – Solar module prices), the premise of this study is that German firms had to upgrade in order to survive. Conclusions from international business outline that the sustainable income development, and thus survival, relates to the capacity to upgrade (Kaplinsky & Readman, 2001). The capacity to upgrade is partly determined by how well a company can use upgrading mechanisms. Since upgrading mechanisms contribute to the development of knowledge bases and subsequently the forms of upgrading (van Tuijl et al., 2016), studying the mechanisms can be perceived as the best way to understand how and why companies survive.

Furthermore, linking knowledge bases with upgrading is an understudied field and has only been done in one previous study (van Tuijl et al., 2016), to the best our knowledge. The recent study of van Tuijl et al. (2016) focused on the symbolic and synthetic knowledge bases, and did not investigate how the upgrading process of the analytical knowledge base takes place. The focus of the study was on within-firm interaction and joint ventures in China, which is a specific case, since China has a powerful government that controls the industry to a great extent and a large domestic market. There is thus a great gap in research regarding knowledge base upgrading and the authors propose that future research should further conceptualise this research by analysing all three types of knowledge bases, investigating the relations with other actors in innovation systems and value chains to the firm, such as clients, knowledge institutes and suppliers, and in countries that have differing political systems to that of China (van Tuijl et al., 2016).

1.3 Aim of the study and research questions

Several German module manufacturers went bankrupt during the early 2010's crisis, but some of them survived. Upgrading has been suggested to be vital to the survival of the firm (Kaplinsky & Readman, 2001). However, upgrading mechanism that sustain companies is not well understood and in order to contribute to the research field of upgrading, this study's aims to investigate the upgrading processes which helped solar module manufacturers in Germany to survive the industrial crisis in the early 2010's. The second aim is to contribute to the research of knowledge base upgrading, further conceptualising van Tuijl et al.'s (2016) framework, investigating how firms' upgrading mechanisms relate to the types of upgrading and knowledge bases. The research questions formed for this study are as follows:

- *What upgrading mechanisms are the most important for German PV module manufacturers' survival?*
- *How do upgrading mechanisms facilitate firms' upgrading and knowledge bases?*

1.4 Limitations of the study

This study focuses on upgrading and how upgrading mechanisms influences industrial manufacturers' survival when there is no possibility to compete on price. The study is limited by country (Germany), by one industry (the PV industry) and one value chain activity (solar module manufacturing). I.e. the study is limited by location, industry and value chain. The results are influenced by industry, location and value chain specifics. Different results might be present in a different country, industry or value chain.

Companies' innovativeness, and thus survival, can also be influenced by other aspects not analysed in this paper. According to Teece (2010), innovation is influenced by, but not limited to: research and educational institutions, customer markets, governmental and judiciary bodies, rival firms, human capital, financial institutions, regulatory and standards bodies, and suppliers and complementors. This research analyses innovation from the perspective of upgrading processes by investigating research and educational institutions, customer markets, rival firms, human capital, suppliers and complementors. Research in policy and financial support is beyond the scope of this paper, hence governmental and judiciary bodies', financial institutions', regulatory and standards bodies' influence on innovation and survival of the firms will not be analysed. Apart from these, other factors might also exist that influence innovation and survival that were not examined in this study.

1.5 Research outline

Theoretical Framework describes the theory used in order to answer the research question and fulfill the research purpose. The framework provides definitions of Dominant Design theory, Types of Upgrading, Upgrading Mechanisms and Knowledge bases. The theory is further critically analysed, providing discussion from different researches and ends with a summary of all theories and a conceptual framework. The following *Methodology* chapter explains and argues why specific method was chosen for analysing and gathering of empirical material. It also outlines what kind of method was used to construct the case study. The *Empirical Background* presents empirical findings gathered from semi-structured interviews from case study respondents. The material is structured and supported by direct quotes from the respondents. After empirical findings are presented, they are analysed in combination of the theory in the *Analysis* part. This in turn creates a discussion and understanding in order to clearly answer the research question. It also provides a discussion and analysis regarding disparities and similarities between the empirical material and theoretical framework. The paper ends with *Conclusion*, where the research question is fully answered and the research purpose fulfilled. The most important upgrading mechanisms for German PV module manufacturers survival are presented and explanation is provided how they facilitate knowledge bases and types of upgrading. Suggestions for further research are provided along with theoretical contributions and managerial implications.

2. Theoretical framework

This chapter outlines relevant literature in the fields of innovation and upgrading. It starts with an introduction about research in firms' survival and the Dominant Design framework, followed by a discussion of the four main types of upgrading, the authors' own conceptualisation of upgrading mechanisms and knowledge base literature. The chapter ends with a conceptual framework, linking the theory used in this paper together.

2.1 Innovation and the survival of firms

The survival of firms has been extensively studied, and research has showed that markets are in constant turbulence with firms entering and exiting the markets (Caves, 1998). Two factors have been proposed to be crucial to the survival probability of firms: size and age. Size has been linked to Gibrat's law of proportionate effects where firms, which set up large scale production from the start, have a lower risk to go out of business (Mata & Portugal, 1994; Geroski, 1995). Age is related to the learning effects of firms and is based on Jovanovic (1982) theory on "noisy selection". According to this framework, firms have no idea of their relative efficiency compared to that of competitors and in the long run the inefficient one exit the market while the efficient ones grow and survive (Jovanovic, 1982). The firm's survival likelihood, thus, increase by the age of the firm.

Ericson & Pakes (1995) have extended Jovanovic's model to include firms' R&D (Research and Development) investments, which is a factor that firms can directly affect themselves. By investing in R&D firms can increase their survival chances through efficiency improvements, leading to profitability growth (Ericson & Pakes, 1995). This have been confirmed by several studies, showing, for example, that R&D expenditure is positively related to survival especially if the firms do not patent (Hall, 1987) and firms face a 57 percent lower exit risk if they invest in R&D, compared to firms that don't (Perez, Llopis & Llopis, 2004).

According to Agarwal and Audretsch (2001) size and age have an influence on firms' survival, however, the importance differs in sectors depending on the industry's stage in the technological life cycle and technological regime. In the earlier stages of technology life cycle, size is more important, as innovation procedures are not routinised, while in the later stages when innovation become routinised, smaller firms can reach success in market niches which are not occupied by incumbents (Agarwal and Audretsch, 2001). This is also confirmed by Colombelli, Krafft & Quatraro (2013), which also state that survival is linked to intentional innovation processes from firms.

2.2 The dominant design framework

The Dominant design framework, also known as the Abernathy-Utterback (A-U) model), is the most influential framework explaining the technology life-cycle. The Dominant Design framework was first introduced by Utterback & Abernathy (1975). It explains the changing character of innovation in industries over time through a three-phase model. Below is a summary of the phases, based on Utterback (1994).

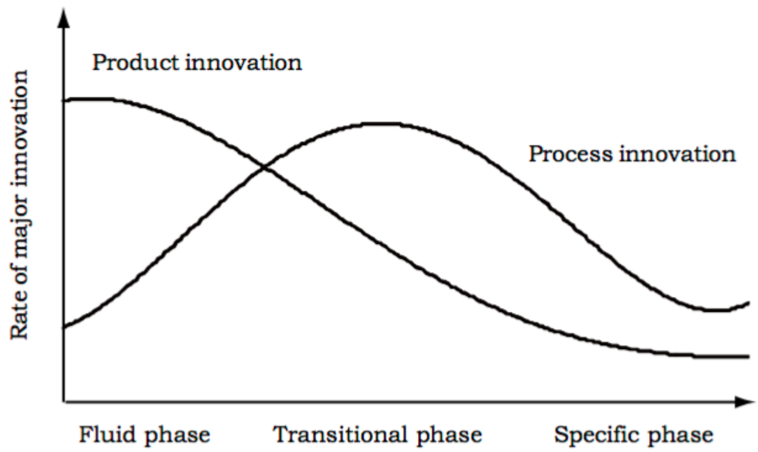

Figure 1. The Dominant Design Model. Based on Utterback (1994)

In the first, *fluid phase,* there is not one single established product technology. Research and development has a diffused focus as it is a great uncertainty of which technology will prevail and product technology is often expensive, unreliable and crude. The market is not established and it is often unclear who the target market is. The competition is based on functional product performance and brand name is of little importance. There are only a few competitors and market shares are fluctuating significantly in the early years. The vulnerability of the market leader lies mainly in imitators, patent challenges and product breakthroughs of competitors. The plants are of small scale and usually in the vicinity of the innovation source or user. The equipment in the plants are of general purpose and require skilled labour (Utterback, 1994).

The *transitional phase,* marks the time when the innovation is beginning to be accepted by the market and a dominant design emerges, however, there is still product variations. The market for the new innovation grows and the focus turns to the factory floor to come up with solutions to mass-produce the product. The needs of the customers become more clear and production targets specific users. The link between product and process innovation becomes more tight. Specialised expensive equipment is bought by the firms and the production process starts to get more automated, while the materials become more specific (Utterback, 1994).

When the innovation reaches the third, *specific phase*, efficiency of the production process is in the focus and the basis of competing is on a quality-to-cost ratio. The similarities of the products are often greater than the differences and the competition is on a standard, mainly undifferentiated, product. Innovation comes in the form of incremental product innovation and cumulative quality and productivity improvements. Product and process are tremendously closely linked in this stage and small changes to either the product and process requires a subsequent change to the other which is often costly and hard to accomplish, as the processes have become automated and rigid (Utterback, 1994). According to Foster (1986), the gains of research efforts diminishes as technologies start to reach technical performance limit. Since competition has moved to a price basis, the production plants are large and there is usually an oligopolic market, with a few dominant actors (Utterback, 1994).

2.3 Dominant design in the solar industry

Huenteler et al. (2016) have researched the technology life-cycle of the PV industry between 1963-2009. Their research show that one design: crystalline silicon, have dominated the market from the beginning of the PV industry’s life cycle. Thin-film module sales did increase during the 1980s and again, moderately, during the late 2000s. However, these trends were short-lived and swiftly reversed, and the market share of crystalline silicon cells has since 1993 always been above 80 percent (Huenteler et al., 2016). In 2015, crystalline dominated the market, with a global market share of around 93 percent (Fraunhofer ISE, 2016).

The technology life-cycle of PV follows the patterns of mass-produced products in the dominant design framework, according to Huenteler et al. (2016). From the early start the innovation was in production, followed quickly by an increase in process innovation. The focus in innovation has thus turned to incremental change, which aligns well with the later stages of the dominant design framework. Critical patented innovations in PV systems have been dominated by cell process innovation since the mid-1980s. Module innovations were relatively important until 1995 and then again shortly in 2002-2003, while innovations in mounting systems and grid connections have been unimportant in changing the trajectory of the technology. In thin-film technologies there is a greater interdependence on product and process innovations, which is why during a period between 1980 and 1995 there were many patents in the technology related to both product and process technology (Huenteler et al. 2016).

2.4 Upgrading

Studies on survival of the firm have largely focused on age, size and to a lesser extent also product and process innovation (Cefis & Marsili, 2006). The current dominant PV technology is in a maturing phase (Huenteler et al., 2016) where product and process innovation is relatively less important and economies of scale and cost of production becomes more important in becoming the market leader (Utterback, 1994).

This led to a shakeout in the PV industry in the early 2010s, which has also been documented in many other industries where the dominance of a standard product led to price competition (Klepper, 2002). Upgrading is a concept which moves away from the view that firms only survive because of their technological capabilities, they also need to alter their functions, moving away from low value adding activities, in order to survive in the long-run. Disembodied activities, such as technology and design can offer higher rates of return for companies and are ways, other than product and process innovation, of escaping a “race to the bottom” (Kaplinsky & Readman, 2001).

Defined simply, upgrading relates to “innovating to increase value added” (Giuliani, Pietrobelli & Rabellotti 2005, 522). Since manufacturing companies in developed countries are encountering increasing competitiveness from the globalised market, they have to increase the skill content of activities or move to market niches, which are protected with entry barriers and are isolated from this kind of pressure (Humphrey & Schmitz, 2002). These activities can be referred to as upgrading. IB, value chain and cluster literature underlines the importance of upgrading as a factor that influences a firm's performance (Porter, 1990; Humphrey & Schmitz, 2002.). Following the definition of Giuliani et al. (2005), upgrading will not be viewed as only new breakthrough innovations in this paper. Upgrading also include marginal improvements which to the firm are new, but are already existing in the market, and allow firms to compete internationally. This includes switching to processes, products, activities and sectors with higher entry barriers, which permits more value added (Giuliani et al., 2005).

Upgrading is a concept, which has been used in many different ways and has been defined differently. It has also been used in different research fields, where it has been referred as "industrial-", "sectoral-" and "economic-" upgrading, or just plainly as "upgrading" (Milberg & Winkler, 2011). This paper focuses on the four categories of upgrading related to the economic performance of the firm: product, process, chain and functional upgrading. Kaplinsky & Readman (2001) suggest in their research that upgrading can be viewed from the whole value chain perspective. For example, product upgrading can relate to manufacturing, marketing or value chain activities at the same time. Moreover, upgrading can occur throughout different parts of the value chain and shifts the general focus on only manufacturing to other activities of the value chain, which are related to supply of goods and services, distribution and marketing. (Kaplinsky & Readman, 2001).

Social upgrading is another category which has recently got a lot of attention in the global value chain literature, looking at improvement of workers conditions in developing countries (Humphrey and Schmitz 2002; Barrientos, Gereffi, and Rossi 2011). Our research is not going to look at social upgrading, because the main focus of this study is survival of companies through upgrading mechanisms. Since, survival is not directly related to social upgrading and since this case context is Germany, which is a developed country, social upgrading is not going to be included in this research.

2.4.1 Product upgrading

Product upgrading involves improving old or introducing new products to the market before rivals. This often entails having skilled labour, which have the ability to develop the product (Kaplinsky & Readman, 2001). Product upgrading can also be viewed as a transition to a more sophisticated product in terms of increased value per unit (Giuliani et al., 2005). For example, moving from generic solar module manufacturing to module manufacturing design for aircrafts, which is lighter, has higher quality and efficiency, but at the same time is much more expensive.

R*egimes of appropriability* is a term to describe the ability of an innovator to capture the innovation's rents. If they are weak it limits the innovator possibility to innovate. Patents, for example, have been shown to rarely works in practice, as well as in theory, and they can often be invented around. Codified knowledge can be transmitted and received with ease, is vulnerable to industrial espionage and can be imitated by competitors (Teece, 1988).

2.4.2 Process upgrading

Process Upgrading deals with the objective of increasing efficiency in the production process through changes. This can entail implementing a higher degree of automation to increase productivity, thereby reducing the need of workers in the production (Kaplinsky & Readman, 2001). It can also be referred as transformation of resources into production in a more efficient way by rearranging and reorganising the production systems or introducing a better technology (Giuliani et al., 2005). Teece (1988) argues that trade secrets is a usable option to patents in industries where innovation comes from processes. This is only viable, however, if a company can commercialise the product without the underlying technology being revealed. Process upgrading usually involves tacit knowledge which is easier to keep secret than codified knowledge, because it depends on know-how that is hard to articulate (Teece, 1988).

2.4.3 Chain upgrading

Chain Upgrading, sometimes referred to as Intersectoral Upgrading, occurs when firms move to a new value chain, e.g. moving from TV manufacturing to computer monitor manufacturing. By switching production, the firm enters new product markets and industries.

These markets may require the firm to use new manufacturing technologies and marketing channels, which demand different innovations and labour force than previously (Kaplinsky & Readman, 2001). It usually implies that companies are moving from lower value added to higher value-added activities where there is less competition (Giuliani et al., 2005).

2.4.4 Functional upgrading

Functional Upgrading refers to changing the activity mix to increase the value added. This can be done in the vertical plane, either by adding or subtracting upstream and downstream activities. For example, adding additional after sales services and/or products to provide higher value-added solution instead of a standardised product. Functional upgrading can also occur through specialisation (Giuliani et al., 2005), e.g. when a company moves from production to design or project planning.

2.5 Upgrading mechanisms

Some scholars refer to *upgrading mechanisms* and use the terminology *knowledge sourcing mechanisms* (Martin & Moodysson 2011). However, according to van Tuijl et al. (2016), upgrading involves knowledge sourcing together with learning. Martin & Moodysson (2011) discuss three upgrading mechanisms that firms may utilise: *Mobility, Monitoring & Collaborations*. van Tuijl et al. (2016) build on this framework by replacing *collaborations* with *formal collaboration* and dividing it up to variables suitable for their research by using: *Learning-by-interacting in project teams, On-the-job training and learning in TNCs, Technology transfer and Learning-by-doing and-using*. We further build on these concepts, to cover more aspects of upgrading mechanisms. van Tuijl et al. (2016) did not include informal collaborations in their research. Informal collaborations have been shown to be very important for firms to obtain new knowledge. Research also signifies that informal collaborations represent an important part in knowledge diffusion (Dahl & Pedersen, 2004). Therefore, we believe that informal collaborations should be included in a framework for upgrading mechanisms. The generic term *collaborations* by Martin & Moodysson (2011), is therefore found to be more appropriate, including both *formal* and *informal* relationships. Further discussions regarding two other mechanisms: *internal* and *acquiring,* and the reasons for choosing to include these in the research is provided later in the paper.

In this paper, we will use a framework which includes the following mechanisms: *Mobility, Monitoring, Collaborations, Internal* and *Acquiring*. Below is a discussion of each of the mechanisms that are used in this paper to analyse the empirical findings and a discussion of why we chose to include these five upgrading mechanisms for this case study.

2.5.1 Mobility

Upgrading through *mobility* occurs when firms source knowledge through recruitment of personnel from the external environment, e.g. other firms or universities (Martin & Moodysson, 2011). According to Almeida & Kogut (1999) interfirm mobility of engineers has an influence on the local transfer of knowledge. Regional labour networks are generating the knowledge flow (Almeida & Kogut, 1999). Since employees are usually the main source of knowledge inside the company, labour mobility is considered to be one of the essential parts for knowledge diffusion and has positive effects on the performance of the companies (Boschma, Eriksson & Lindgren, 2009). A study by De La Tour, Glachant, & Ménière (2011) signifies the high importance of employee mobility in the PV industry in developing markets. They concluded that one of two main ways of how Chinese PV companies were able to transfer technology and gather important skills and capabilities was through local and international employee mobility and recruitment of skilled executives. These executives were able to create the first companies in the Chinese PV industry, taking advantage of China's comparative advantage of cheap labour and energy in the PV module and cell industries (De La Tour et al., 2011).

Labour mobility has a positive effect on productivity increase when it involves mobility of employees with related skills and competences. Labour mobility by itself does not positively impact a company's performance, it highly depends on skills that flow into the company. Only a portfolio with related competences increases productivity and growth of the manufacturing company, in contrary to portfolios that just consist of similar competences or unrelated competences. In other words, inflow of related skills has a positive effect on performance and inflow of unrelated or similar skills has a negative impact (Boschma et al., 2009). Therefore Boschma et al. (2009) suggest that there is a inverted U-shape relationship between performance and competences, where both too similar and too different competences negatively affect the firm, while the equilibrium in between them has a positive affect.

It is also important to mention that labour is one of the most immobile production factors. In general, people tend to stay in their home region and are not considering to leave. There is a negative relationship between intention to change location and the duration of stay in the home location (Gordon and Molho, 1995; Eriksson, Lindgren, & Malmberg 2008). Labour thus can be considered an asset that is tied to location and can be seen as sunken cost if moving away (Fischer et al., 1998).

2.5.2 Monitoring

Monitoring as an upgrading mechanism explains how firms source knowledge from the external environment by observing competitors, customers and suppliers (van Tuijl et al., 2016), this can happen without any direct interaction (Martin & Moodysson, 2011). Monitoring is similarly described in marketing research. Marketing research refers to this concept as market orientation and links it to organisational learning activities (Kohli and Jaworski, 1990; Narver and Slater, 1990). This form of organisational learning arises when companies are able to adapt market knowledge and adjust it in order to respond to quickly changing external market factors (Loon Hoe, 2008). Market orientation describes how market knowledge is controlled through knowledge gaining activities such as conducting marketing surveys and arranging discussions regarding market trends. It also involves constantly reviewing products and services in order to provide the best solutions to customers (Loon Hoe, 2008).

Market orientation underlines the importance to focus on customers and competitors, and internal functional activities that are affecting business success (Han, Kim & Srivastava, 1998; Mavondo, Chimhanzi & Stewart, 2005). Day and Wensley (1983) discussed in their research that competitor and customer orientation is an essential factor for competitive advantage in the market (Han et al., 1998; Mavondo et al., 2005). Market knowledge is a crucial organisational asset created by combining knowledge from customers and competitors (Maltz & Kohli, 1996; Srivastava, Fahey & Christensen, 2001). Companies focus on gaining knowledge about customers and competitors in order to create higher value for the customer (Day, 1994; Farrell & Oczkowski, 2003; Sinkula, 2002; Slater & Narver, 1995). Following this discussion, monitoring can be seen as vital for the competitiveness and survival of the firm.

2.5.3 Collaborations

Collaborations deals with the direct interactions between actors in the environment. Studies in the subject often focus on innovation systems and value chain interactions. Learning by interacting between various actors in the economy have important influences for competitive and comparative advantage. It is especially influential where technology is complex and developing, and there is a need for close communication, collaboration and interaction between different customers and manufacturers of the technology. The process usually involves learning and modifying of existing or creation of new technology. This allows to increase the competitive position of the company. Moreover, these relationships are more likely to occur within borders than across. That is the reason why it affects comparative advantages of countries as well (Lundvall, 2010).

Jensen et al (2007) contrasts two different modes of innovation. One is based on use of codified, technical and scientific knowledge. The other relies on informal processes, learning by interacting and know-how based on experiences. The study concludes that companies that are able to combine these two modes are more likely to benefit by innovating new products or services than those companies, which rely on only one mode or another. To cope with radical improvements in products and processes, companies need to implement learning by doing, using and interacting. At the same time, companies that are able to connect to sources of scientific and codified knowledge are able to benefit from new solutions, stay competitive and develop new products. Innovation performance is thus increased with the combination of two different modes. Thus, in order to benefit from important gains from developing technology and a science base, companies should be also adopting practices and measures in order to promote informal learning by using, doing and interacting. According to the study, these implications should be used in order to benchmark different innovation systems and policies (Jensen et al., 2007).

2.5.4 Internal upgrading mechanisms

Internal upgrading mechanisms such as Learning-by-doing and -using have gained a lot of attention in innovation studies. This type of upgrading can be achieved by e.g. trial-and-error production, testing and experimenting, which to a large extent takes place in-house (Pan &

Li, 2016). Learning by doing and using are the essential forces that drive incremental process of innovation. Virtually in all of the fields of production of goods, constant repetition of manufacturing tasks tends to lead into a steady improvement of the efficiency of manufacturing processes and product design, and performance (Landes, 1972). That is the reason why the importance of learning-by-doing and -using processes are an essential source of innovation. Moreover, intra-organisational flows of knowledge, the amount, type and directions of knowledge flow across organisational borders are affecting company's performance (Yamin & Otto, 2004). The influence of internal knowledge flows on company's performance is even stronger compared to that of informal collaborations (Pan & Li, 2016).

According to Stadler (2011) internal trial and error innovation is the main mode of innovation in process oriented settings. Incremental innovation accumulates to larger innovations over course of time (Stadler, 2011). Hatch and Mowery (1998) also discuss the impact of learning by doing for process innovation in the semiconductor industry. The authors highlighted the improvements in production performance through a learning by doing approach (Hatch and Mowery, 1998). A study by Beneito & Sanchis Llopis (2015) also shows that learning by doing is essential when companies organise R&D activities. Moreover, companies can benefit from external R&D activities only if those activities are related to internal R&D (Beneito & Sanchis Llopis, 2015). The literature clearly suggests that internal company activities, such as learning by doing (trial and error) have substantial effect on innovation and manufacturing processes, which is the reason why we chose to use internal as an upgrading mechanism.

2.5.5 Acquiring

Firms do not always monitor or collaborate with the external environment in order to increase their innovativeness, in many cases, knowledge is gained through *acquisition* of other firms, technologies, patents etc. Research states that companies can grow their knowledge bases through acquiring of external knowledge bases and through various knowledge enhancing investments (Cohen and Levinthal, 1989; Huber, 1991). Studies show that technical knowledge and development of technical capabilities are becoming more and more important reasons for acquiring. (Link, 1988; Granstrand et al., 1992; Ahuja & Katila, 2001). Also, the role of acquisitions is important for growing companies knowledge bases (Granstrand and

Sjolander, 1990; Huber, 1991; Gerpott, 1995). Acquisitions affect the company's innovation through two possible ways. Firstly, acquisition of another company can be seen as absorption of another company's knowledge bases. Such absorption expands the company's knowledge bases and increases the innovation output by enhancing the potential for innovative combination of acquired and existing knowledge and providing economies of scale and scope (Henderson and Cockburn, 1996; Fleming, 2001). Secondly, acquiring of knowledge may increase a company's overall absorptive capacity. As a company expands its internal knowledge bases and technological capabilities, it also increases its abilities to utilise and absorb external knowledge bases (Cohen and Levinthal, 1989). When a company acquires knowledge bases it also gets access to external knowledge domains that are used and understood by the acquired company. That is the reason why acquisition increases internal and external knowledge base elements, and thus allows for the recombination of knowledge bases (Ahuja & Katila, 2001).

Qiu, Ortolano & Wang (2013) investigated the Chinese wind turbine industry and the factors that influence technology upgrading, and concluded that technology acquisition mechanisms are extremely significant factors that influence technology upgrading. Technology acquired through production licensing has the lowest impact on upgrading and a technology acquired through joint design has the highest (Qiu et al., 2013). Transferring machinery and equipment from other firms can also upgrade a firm's capabilities (Qiu et al., 2013). The study by De La Tour et al (2011) also investigated drivers of success of PV module manufacturing industry in China with special focus on the role of innovation and technology transfer. The study concluded that one of the two most important ways how Chinese PV module producers gained technologies and skills was through acquiring of equipment.

In general, acquisitions facilitate technological capacity of the company by increasing the innovation capacity (Ahuja & Katila, 2001). The ability to acquire new knowledge is an important element for effective innovation (Smith & Sharif, 2007). Following the above discussion, which shows that acquisitions can play a major role in upgrading a firm's capabilities, we have chosen to include it as a mechanism in our study.

2.6 Knowledge bases

Literature suggests that innovation is influenced on different knowledge inputs. It involves combinations of synthetic, analytical and symbolic knowledge (Grillitsch et al., 2016). Thus, it is important to differentiate and define different knowledge bases in order to have a better understanding how knowledge influences upgrading.

2.6.1 Definition

Innovation differs quite substantially among different industries and sectors, which require specific knowledge bases (Asheim & Gertler 2005). Different knowledge bases are used, depending on various types of talent in different phases and modes of innovation process (Asheim & Hansen, 2009; Moodysson, Coenen & Asheim, 2008). In general, knowledge base refers to the knowledge itself and knowledge embodied in techniques and organisations (Brink et al., 2004). Knowledge bases usually contain different combinations of codified and tacit knowledge. These combinations depend on the organisation's or industry's requirements, their usage of skills, the industry pressures and the innovation challenges (Asheim & Hansen, 2009; Moodysson, Coenen & Asheim, 2008).

2.6.2 Analytical knowledge

Analytical knowledge refers to activities where innovation is created by new knowledge. Knowledge is created by the use of rational and cognitive processes, such as formal models and scientific knowledge is of great importance. In their innovation process, firms with an analytical knowledge base often establish and utilise their own R&D departments, as well as making use of research from universities and other research organisations (Coenen et al., 2006). Thus, linkages to research organisations and networks are of great importance for the firm (Asheim, Coenen & Vang-Lauridsen, 2007; Coenen et al., 2004). Since scientific knowledge dominate, the knowledge is often codified through publications and patents documentation. As the data is codified, there are high requirements of a highly skilled workforce in the R&D department with analytical skills to be able to interpret the results and theory creation, concepts, scientific experiments are usually required. Employees therefore often have an academic background (Asheim, Coenen & Vang-Lauridsen, 2007; Coenen et al., 2004).

The nature of scientific knowledge, as codified and abstract, often readily available in public conference papers and journals, means that face-to-face conversations would seem to be of lesser importance to gain access to the knowledge. This is not, however, always the case since many firms compete on accessing and absorbing the information before their competitors to gain a competitive advantage and face-to-face communication can make access and absorption easier (Asheim et al., 2007). For example, face-to-face communication has been shown to facilitate brainstorming, spawning of ideas and trust-building among researchers (Moodysson, Coenen & Asheim, 2008). Cluster formation or closeness to research organisations, such as universities, with state of the art research for their field is common of firms working in analytical industries (Cooke, 2005). The face-to-face communication should despite this not be overestimated for acquiring analytical knowledge, because of the communication being codified (Asheim et al., 2007).

2.6.3 Synthetic knowledge

Synthetic knowledge can be defined as innovation through applying or combining existing knowledge. The process is often inductive where engineering knowledge is important (Asheim et al., 2007) and knowledge creation mostly occur by practical work, experimentation, testing and computer simulations (Pavitt, 1998; Vincenti, 1990). For example, specific issues that come up when interacting with suppliers and clients are often solved with synthetic knowledge (Vang & Overby, 2006). Applied research is fairly common, but even more common is R&D focusing on process and product development. In applied research developments, research organisation often play a relevant role, but less so in process and product developments. Because synthetic knowledge often is a result through learning-by-doing, -using and -interacting by experience from the worksite, tacit knowledge appears to play a larger role than for analytical knowledge (Johnson, Lorenz & Lundvall, 2002). Craftsmanship, know-how and practical skills are needed for the creation of knowledge and these skills are often acquired by on-the-job training and through specific expert education in specific schools. Modifying current processes and products are common, as the outcome of the process is often geared towards incremental innovation, such as increased reliability, efficiency, user-friendliness and practical application of the product (von Hippel, 2005).

Face-to-face interaction is very important in industries with a synthetic knowledge base, because of the tacitness of the know-how and the custom solutions. Interaction between, and input from, users and producers is crucial as the process is many times of a trial-and-error variation, which calls for close cooperation face-to-face (Thomke, 2003). By working face-to-face, the knowledge exchange is easier and faster, since the tacit knowledge of the involved parties can be synthesised and discussions about what has been done and what needs to be done to solve the specific problem at hand can be facilitated. Because of the focus of incremental innovation and working with suppliers and customers, physical proximity to universities tend to be of lesser importance. To take advantage of the innovative possibilities of working close and having regular face-to-face interactions with suppliers and customers, cluster formations in synthetic industries are, on the other hand, frequent (Asheim et al., 2007).

Gress (2015) study on the solar PV industry in South Korea focused on the importance of analytical and synthetic knowledge in the industry. The results suggest that synthetic knowledge being more important than analytical knowledge. According to the Gress (2015) study, companies in the PV sector usually place importance on problem solving together with customer and supplier interactions. The research indicates that customer and supplier relationships have an impact on companies' innovativeness. PV manufacturers tend to invest in both, internal and external R&D and bring incremental innovations through synthetic knowledge bases (Gress, 2015).

2.6.4 Symbolic knowledge

Symbolic knowledge is used through generation of meaning and desire, aesthetic features of product design, images, symbols and the use of cultural artifacts. Symbolic knowledge is increasing in importance through product advertising and design. Narratives and visual appeal are often used as means to add value to the products. The most important part of symbolic knowledge creation process is generation of new ideas and visuals; thus, activities require innovation and design capabilities (Asheim & Hansen, 2009). The market for symbolic knowledge focuses on customers' dreams and visions. Companies working with symbolic knowledge bases are manufacturing objects with spiritual and intellectual substance. That is the reason why these businesses then tend to focus on *sign-value* of intangible symbols, brands, images, designs, rather than the tangible aspects that provide *use-*

value (Lash & Urry, 1994). Companies thus compete more on value of brands and signs than on value of actual products and their features. Symbolic knowledge creation focuses on learning by doing approach and on job training, is usually carried in project groups and through interaction with other people in specific communities. That is why informal industry cooperations in professional community are important. In order to benefit from industry cooperations and the professional community companies have to "be there" and take part in related activities. Context, fashion trends and tastes are central part in symbolic knowledge development. The knowledge is usually closely tied to deep understanding of habits and norms and everyday culture of different social groups. That is the reason why symbolic knowledge is related to unique tacit component, which is related to cultural embeddedness, interpersonal interactions and aesthetic input (Asheim et al., 2007). Monitoring the market has also been found to be important to develop a symbolic knowledge base (van Tuijl et al., 2016). Symbolic knowledge, in general, contributes substantially to innovativeness, not only in those industries that are dominated by symbolic knowledge base (fashion, tourism or new media), but also in industries that are described as synthetic or analytical sectors, such as food and drinks or biotechnology and pharmaceuticals (Asheim et al., 2007).

Symbolic knowledge development occurs through means of artistic, open-ended, creative and communicative thinking and interactions that are not related to specific rules and norms and usually consist of re-interpretations of established conventional ways (Manniche & Larsen, 2013). The importance of personal contacts creates high spatial proximity amongst project partners that are generating knowledge by learning from each other and sharing ties (Grabher, 2001). Symbolic industries are strongly related to the local context, networks and knowledge flows are locally established and companies are usually having less formal knowledge sources. Localised learning is essential, because knowledge is highly variable between place, gender, class and other bound and complex factors of influence. Informal interactions are at the center of the symbolic knowledge flows, however, universities may also be important, because they can provide a platform for network formation and informal contacts (Martin & Moodysson, 2011).

2.6.5 Combination of knowledge bases

Recent research in knowledge base theory has largely moved away from viewing different kind of knowledge bases in isolation and competitive advantage in industries stemming from one kind of knowledge base. Rather, it has been proposed that combinations of knowledge bases are important for the competitive advantage of the firm (Grillitsch et al., 2016; Martin & Moodysson, 2011; Manniche, 2012; Strambach & Klement, 2012). According to the research, combinations of knowledge bases support innovation of companies. This is especially true for symbolic knowledge, which by itself has no effect for innovation of the company. However, combining symbolic knowledge with analytical facilitates innovativeness of the company. Moreover, clear synergies have been found when combining synthetic and analytical knowledge in house (Grillitsch et al., 2016). Furthermore, since analytical knowledge is usually residing in the external region, absorptive capacity plays an important part for innovation (Cohen & Levinthal, 1990). Regional synthetic knowledge only facilitates innovation of companies that have strong analytical knowledge foundation. Innovation outcomes, in general, are related to the diversity and combination of knowledge inputs, which can be viewed through different knowledge bases. Innovation, thus, in many cases relates to various combinations of analytical, synthetic and symbolic knowledge. It is a result of not only science based knowledge, but also from arts-based experience and engineering know-how. According to recent studies in the field, symbolic and synthetic knowledge are relevant for innovation not by themselves, but together with other knowledge bases (Grillitsch et al., 2016). Literature also suggests that companies should seek to open up local-global spectrum for interaction possibilities through different knowledge bases, rather than focusing or prioritising one specific interaction. The literature also outlined and analysed different combinations of such interactions that have to be maintained in order to increase innovativeness (Gress, 2015). In general, combining different knowledge bases is a challenging and complicated process. It involves unification of separate knowledge bases that are spreaded over a variety of different actors. Particularly, the difficulties when implementing collaborations among firms are apparent. In order to coordinate knowledge combination process, different actors usually together develop their own structures for governance (Strambach & Klement, 2012).

2.7 Conceptual framework

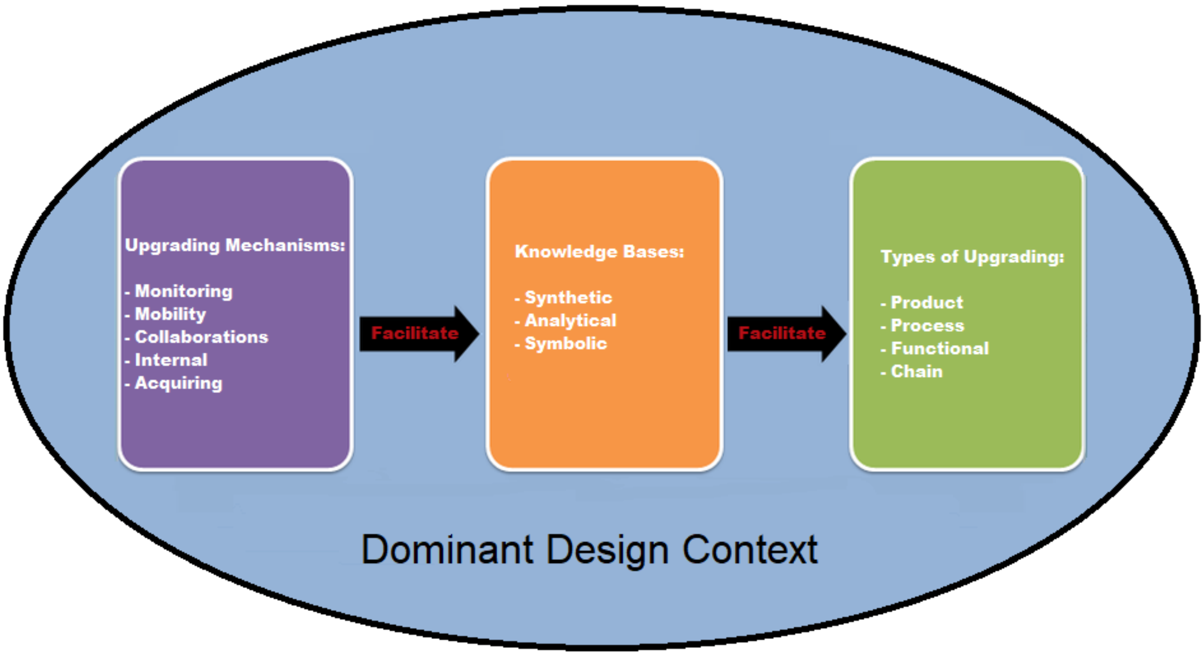

Figure 2 Conceptual Framework

Compiled by authors

The conceptual framework in *Figure 2* represents how different theories outlined in the research relate to each other. The framework shows how upgrading of firms' capabilities can occur. The drivers of this upgrading are the upgrading mechanisms. Van Tuijl et al. (2016) have shown that knowledge bases can be upgraded through the use of upgrading mechanisms. Furthermore, increasing a firm's knowledge bases can lead to an upgrading of the firm's capabilities (type of upgrading). These relationships are shown by the arrows going from upgrading mechanisms to knowledge bases and to the types of upgrading. The circle around is showing the context of the phase in which the industry is in according to the dominant design framework. This has been deemed important to include, since the dominant design framework explains that the relative importance of different innovative activities fluctuates throughout the technological lifecycle of a product (Utterback, 1994). Hence, the types of upgrading will likely be of varying importance depending on which phase the technology is in, which will affect what upgrading mechanisms firms' utilise and what knowledge bases are subsequently upgraded.

3. Methodology

This chapter outlines the research method used in the paper and the justification of this method. It provides a detailed account for how the data gathering was conducted and how the credibility and validity was assured throughout this study.

3.1 Scientific approach

The research is based on hermeneutics, where the material is analysed according to the theoretical framework. The core principle of hermeneutics is that the analysis of the text should bring meaning to the text from the author's perspective (Bryman & Bell, 2011). This approach is arguably necessary when a real international business case is studied (Piekkari & Welch, 2004). The purpose of the research is to compare theory with the findings by analysing what kind of upgrading mechanisms are the most important for the survival of solar module manufacturing companies in Germany when they no longer can compete on price. The goal of the study is through a hermeneutical approach establish *patterns of interpretation.* Or, in other words, to find a consistent direction of interpretation in the sense that it agrees with already existing theories and other patterns of interpretation in an alike area, or has logical reasons to *not* agree with them. The pattern of interpretation seeks to establish facts from the material (Alvesson & Sköldberg, 2009). In this research case, pattern of interpretation allowed to draw conclusions, fulfill the purpose of the study and the answer research questions. During the empirical material collection and analysis researchers were able to notice similarities, relationships between respondents' answers and draw conclusions relating to the theory.

3.2 Research method

3.2.1 Qualitative

Qualitative research, as in this case study, is often used in studies to explain and analyse complex issues. A qualitative research strategy usually encompasses words rather than numbers in the empirical collection process and data analysis. It looks at relationships between the research and the theory and is primarily explorative research to gain understanding of motivations, underlying reasons and opinions (Bryman & Bell, 2011). Qualitative research also has it limitations. It is strongly dependent on the researcher's skills and heavily affected by personal biases. Moreover, the researchers, as in this case study, usually have to be present during data gathering of qualitative research and it might affect respondents' answers (Anderson, 2010).

3.2.2 Justification of the choice of research method

Despite previously mentioned limitations, qualitative research was determined to be the best method for this case study. The purpose of this research paper is to analyse what upgrading mechanisms are important for companies' survival when they cannot compete on price anymore in the global market. A qualitative approach allowed the authors to fulfil the purpose of the study and to answer the research question, investigating thoroughly which upgrading mechanisms are the most important for the survival of German PV module manufacturers. It allowed the authors to create a detailed description of assumptions, relationships, definitions and general concepts (London & Hart, 2004). The qualitative research method helped to describe the observed reality and present results based on the German solar industry context, relating to the upgrading theory. It also allows researchers to develop profound illustrations of experiences from the information gathered in order to describe the case phenomenon (Merriam, 1998). Lastly, the case study consists of participants, which have different technology and knowledge bases, which cannot be summarised in quantitative data. The case study participants were also sensitive regarding disclosing any kind of quantitative data, thus qualitative research was chosen.

3.2.3 Abductive research

Research can be inductive, deductive or abductive, which depends on the way the researchers want to develop the research. Inductive research is when the empirical material creates the theory. Deductive research is used in order to test the theory with the empirical material and then a specific case is developed from the conclusions. The abductive research is a mixture of both approaches. With an abductive approach, the researchers are independant from the theory and they can also combine and change the theory in order to find patterns and concepts in the empirical findings (Alvesson & Sköldberg, 2009).

Theory was used before empirical material collection (in order to form the interview guides) and after the empirical data collection (in order to analyse, apply and use empirical data), thus it led to abductive research approach.

3.2.4 Literature sources

In order to strengthen empirical findings, secondary literature sources were used in this research project. Secondary sources included: scientific databases, scientific journals, books and search engines. Using secondary sources helped the authors to understand and analyse existing theory in the field of upgrading and find theory gaps. This in turn allowed to use the empirical findings from the study in order to contribute to the existing theory in the field. Literature sources in this research project were used in order to demonstrate already existing scholarly reviews. (Bryman & Bell, 2011).

3.3 Method for empirical material

3.3.1 Primary sources

Primary data is collected from the original sources by interviews, observations or surveys (Adams et al., 2007). It can be seen as material for the development of theoretical ideas by actively mobilising and problematising the frameworks that already exist (Alvesson & Kärreman, 2007). Primary data collection is an essential part of this research, because it is the main material used to answer the research questions together with supporting theory. In order to gather primary data in this research 13 interviews were conducted. Out of total 13 interviews, 9 were conducted with solar module manufacturers. Since the total amount of existing solar module manufacturing companies in Germany is very small, 9 interviews covered more than one third of the total available solar module companies and allowed to gather valid empirical material to establish conclusions and patterns. The other 4 interviews were conducted with industry experts in order to reduce biases and form a general outlook. In order to create a better understanding about a complicated subject, which is PV module manufacturing industry in Germany (Yin, 2014) a case study approach was chosen. The research focuses on one specific country (Germany), one specific industry (the PV industry), one specific value chain of the industry (solar module manufacturers), one specific period (the crisis in solar industry in Germany that occurred in early 2010's) and one specific topic, which is the impact of upgrading on companies' survival, thus the research is a very concrete and specific *case study research.*

3.3.2 Choice of sample

In the beginning of the primary data collection, every solar module manufacturing company in Germany that had a working website, to the best of our knowledge, was contacted. In total, 60 solar module manufacturing companies. The companies were found through an extensive search of online company directories, trade associations' websites, photovoltaic interest groups' websites etc. A correspondence with a German trade association was also established via phone and email, to confirm that the module manufacturing companies found in the search represented the existing manufacturers in Germany.

At first, e-mail invitations to participate in the interviews with a general introduction about the research were sent, followed by phone calls. However, only a few companies accepted the invitations. After the initial contact, it became clear that out of 60 solar module manufacturing companies in Germany that are still having their websites running, only 25 companies are actually manufacturing in Germany and are still having ongoing business activities inside the German industry. As stated earlier, out of 25 available companies, 9 agreed to participate in the interviews.

Some companies were not manufacturing solar modules in Germany, they were importing them from China or outsourcing production as OEM (Original Equipment Manufacturing) and distributing or installing modules in Germany under brand image of *Made in Germany*. The research focus was placed only on companies that are actually having manufacturing facilities in Germany and producing modules in Germany, thus after contacting a company and the company representative would confirm that the company is not manufacturing in Germany in its own facility, it would not be included in the research sample. With regard to research institutes, only institutes that have direct relationships with solar module manufacturers in Germany and are located within German borders were chosen to participate in the study

To summarise, in order to form a better understanding and the whole picture of the German solar module manufacturing industry, 13 semi-structured interviews were set with:

- 4 companies operating in the thin-film solar module manufacturing industry;
- 5 companies operating in the crystalline silicon solar module manufacturing industry;
- 3 industry experts from research institutes that are focused on solar module manufacturing;
- 1 industry expert from a silicon supplier;

The Managing Directors or Research and Development Directors were targeted, because they were believed to have the most knowledge about the company's strategic development and innovation. With regard to research institutes, only representatives, who are responsible for the PV part of the institute were interviewed. All interviewees are currently working in Germany and are part of the German solar module manufacturing industry.

In the period between 2017-03-08 and 2017-03-17 four scheduled interviews were completed by phone and nine were completed face to face, on site, at the institutes' and companies' offices in Germany. All interviews involved one person from each organisation with one exception when a group interview was carried out with three directors (Finance, Marketing, R&D) from the same organisation. All interviews were carried in English, and the company and institute representatives had no difficulties to express themselves in a foreign language. Before the interviews were conducted each interviewee received an interview guide with the main questions.

3.3.3 Sample choice justification

Particularly solar module manufacturing companies were affected by increasing competition from Asia, as compared to the other companies operating in the other parts of the PV value chain. For example, solar module equipment manufactures were not affected by crisis as much, because Chinese are still importing and using German equipment and they are not forced to *change* because of the decreasing prices in the market. Also, solar module manufacturing companies have experienced the strongest loss in the market share compared to other members of the PV value chain.

The crisis in the German PV industry that occurred in the early 2010's is a perfect case of which to investigate what upgrading mechanisms are the important for survival of industrial manufacturers working in an international market where they no longer can compete on price.

Solar module manufacturing companies had experienced the strongest effect of the crisis and had the strongest pressure to use upgrading in order to create value added in their offering. That is the reason why this research focuses on German solar module manufacturing companies and not on other parts of the value chain.

Both dominating technology branches for solar module manufacturing process were chosen to be investigated (Crystalline Silicon and Thin-film). This choice reduced biases and allowed to look at both manufacturing process from different perspectives and compare different ways to upgrade. Since companies tend to show only the positive aspects of their own technology, having two different technologies in the research sample allowed to form a more holistic view by receiving both negative and positive information regarding both technologies from the respondents. Moreover, the main focus was to investigate the most experienced and the most knowledgeable companies in the field, which was found to best be accomplished by including both technologies. Furthermore, in order to create higher validity for the research, research institutes and silicon supplier were interviewed as industry experts. This allowed forming even better understanding of the industry and investigating factors that determined solar module manufacturing companies' survival.

3.4 Empirical material collection

3.4.1 Qualitative interviews

As stated before, interviews were carried in two different types: *face to face interviews and phone interviews*. Both types have their own advantages and disadvantages. The main advantage of live interviews is that communication from the interviewee is much better, body language can be used along with different kind of illustrations, it is easier to understand and hear each other and there is no risk of technology failure (Blumberg, Cooper & Schindler, 2011). However, the disadvantage of face to face interviews is the time and labor intensity, and also the cost of traveling. Telephone interviews are on the contrary much less labor intensive, they require less time and financial resources for traveling and are not dependent on place (Bryman & Bell, 2011). The majority of interviews were done face-to-face and some were done over the phone, because of limited respondents availability and time constraints.

Semi-structured interview guides were used and semi structured interviews were conducted. Semi structured interviews mean that the interviewers have the chance to modify the sequence of the questions, ask additional follow up questions regarding topics or statements that appeared significant and extraordinary. At the same time the interviewers maintained similar structures of all the interviews (Bryman & Bell, 2011).

There was a slight variation in the interview guides for the research institutes and for the silicon supplier, because these organisations are not manufacturing solar modules by themselves, but are closely related to the module manufacturers. For example, some questions, regarding the module manufacturers, were asked in a third person format to the industry expert. In total, there were three slight variations of the interview guides (Appendix 11.2, 11.3, 11.4) used, however, they all had similar structure and were alike.

3.4.2 Execution of empirical material collection

All the interviews were carried out according to the semi-structured questionnaires, which were sent approximately one week prior to the interviews to all participants of the study. This allowed the participants of the study to think through the questions and prepare their answers. The questions were based according to the semi-structured interview guide, however, follow-up questions had slight variations depending on the organisation representative answers, its activities and technology. The organisations had variations in the activities they conducted, thus follow up questions had to be formed differently in each interview, however, this has not caused any damage to the legitimacy of the study. On the contrary, it provided concrete examples about upgrading mechanisms that companies and research institutes presented according to their technology, knowledge and innovation activities.

Both interviewers asked questions and participated in all of the interviews (including phone interviews). However, one interviewer was setting the phase and plan, asking some follow up questions and the second interviewer was focusing only on listening, body language and asking only follow-up questions. This division of labor in the end proved to be efficient and provided good empirical material. It allowed to follow the agenda in a logical way, not jumping from one subject to another and back to the first one.

After all the interviews were complete, the recordings of the interviews were turned into transcribed texts and the transcribed texts were checked twice for errors by re-listening to the recordings. This was, of course, time consuming, but also allowed to have precisely accurate quotes and answers from the interviewees. Moreover, this method allowed for both of the researchers to listen to the recordings, and think about the respondents' answers. Transcription, proofreading and correction of the transcribed texts also formed a very good understanding of the material for both researchers.

3.5 Method for empirical material analysis

3.5.1 Template analysis

Analysing the material of the research might be very time consuming and demanding, however, since both of the researchers were very familiar with the theoretical material and had the interviews fully transcribed, it was deemed efficient to follow *the template analysis*. The template analysis helps to arrange the material in specific logical structures (Saunders, Lewis & Thornhill, 2003).

A matrix was created, according to template analysis, by going through transcribed texts again, this time not listening to the audio material and making corrections, but marking different research themes with different colors and then coding the essential parts into the matrix. Coding refers to creating categories, which have specific properties and later can be turned into concepts. Research data is assigned to a specific category and in a similar way category is constructed from the available data (Alvesson & Sköldberg, 2009). Working with this kind of method helps to find clear patterns and linkages according to different classifications in the research material (Saunders et al., 2003). This also follows the hermeneutical science method, as described before, and allows understanding, interpreting and constructing the material in an efficient manner following the theory.

The themes and classifications of the material in the matrix were created according to the theoretical framework and according to the patterns that were already appearing when transcribing the texts.

3.5.2 Credibility of the findings

It is important to stress the high validity of the research sample. The nine companies that were interviewed are the leading solar module manufacturing companies in Germany. Only a few large remaining solar module producers declined our invitation to participate in the research. Moreover, in order to increase credibility and decrease biases industry experts were interviewed and companies from two different technology fields: crystalline silicon and thin-film. Furthermore, most of the interviews were face-to-face, recorded, transcribed and coded in order not to miss any of the important details. What is more, only knowledgeable company representatives were interviewed: CEOs (Chief Executive Officer), Technology-, Finance-, Marketing Directors etc. The company representatives were chosen based on their knowledge about the solar industry in Germany and the knowledge about the company's history, competitive advantage, product development, technology and the knowledge about collaborations between the company and other organisations within the German solar industry. Respondents that were not knowledgeable in these fields were not chosen for the interviews. These qualities were confirmed by phone conversation and / or e-mail by the representatives themselves

3.5.3 Execution of the analysis

As stated before, all the interviews were transcribed and recorded with the exception of one interviewee, who asked no recording and thus only notes were taken. After the transcription, the material was proof read one more time. Later empirical material was marked with different colors and coded according to the theoretical framework. A template method was used in order to better analyse the material and to create overall picture about the case study. The analysis of the empirical material produced more fruitful insights, which helped tremendously to answer the research question fully with supporting arguments and quotes from the empirical material.

3.6 Ethical position

The research project focused on maintaining the main ethical principles throughout the whole research project:

- making sure there is no possible harm caused to the research participants;
- ensuring that there is no lack of informed consent;
- ensuring privacy of each participant;
- absolutely avoiding any kind of deception and being fully transparent both to the reader and to the participants of the study (Bryman & Bell, 2011);

In order to avoid any possible harm to the participants and their organisations, interviewees were informed beforehand about the questions they were going to be asked and about the main topics of the research. As stated before, the interview guide was sent approximately one week prior to every interview. Later, participants were asked to confirm their participation in the research and to confirm that they have actually read and received the interview guide.

Since the solar module manufacturing industry is very competitive, the participants of the study were informed that they were free not to answer the question if the information is confidential and could not be used in the study. Gladly, all of the participants were open and agreed to answer all the questions.

Before the start of every interview, the participants would be asked if they agree that the information they are going to present is going to be published in the research paper and whether or not the interviews can be recorded. Two of the respondents asked to be anonymous in the study, we therefore chose to keep all of the names of the respondents anonymous. Recording of the interview allowed the researchers to focus on the interview itself, there was no need to take notes of the answers, because the recording later was transcribed and relistened two or more times. One interviewee, however, asked for no recording, thus taking notes was necessary.

4. Empirical background

This chapter presents a background of the solar module manufacturing sector. The chapter starts with an introduction to the manufacturing process of solar modules. It is followed by an outline of the recent developments on the German PV market and the consequences for the sector. The chapter provides a context through which the empirical findings can be understood better.

4.1 Solar module manufacturing process

The solar module manufacturing process involves multiple steps and usually follows two main technologies: thin-film or crystalline silicon as illustrated in the figure below (Figure II). Manufacturing process of thin-film solar modules is much shorter as compared to crystalline silicon solar modules. Also, thin-film technology requires solar module manufacturers to complete much more steps by themselves in order to manufacture the module. For example, crystalline silicon module manufacturers are usually buying already made solar cells and combine them into the module, however, thin-film technology is based on deposition processes, thus solar module manufacturers have to rely on their own technology and deposit on glass or plastic (Green Rhino Energy, 2013; De La Tour, Glachant & Ménière, 2011). The difference of complexity in technology between crystalline silicon and thin-film module manufacturers will be important later in the research paper.

As can be seen in the picture, the whole crystalline silicon PV value chain starts from sand, which is later purified into silicon and ends to full functioning solar system that produces electricity. There are also equipment manufacturers that are manufacturing equipment for solar module producers and by doing so contribute directly to the end of the value chain also, however, this research only focuses on solar module manufacturing companies that are in the end of the value chain, right before installers and distributors.

A PV module manufacturer, in general terms, can be defined as a company which manufactures a PV module capable of producing electricity with the photovoltaic effect. Some manufacturing companies outsource a fraction of their production capacity to an OEM or contract manufacturer, but sell it as their own brand name, however, this paper is not going to research these kind of companies. The focus is only on companies that manufacture PV modules by themselves (Mulvaney, 2015).

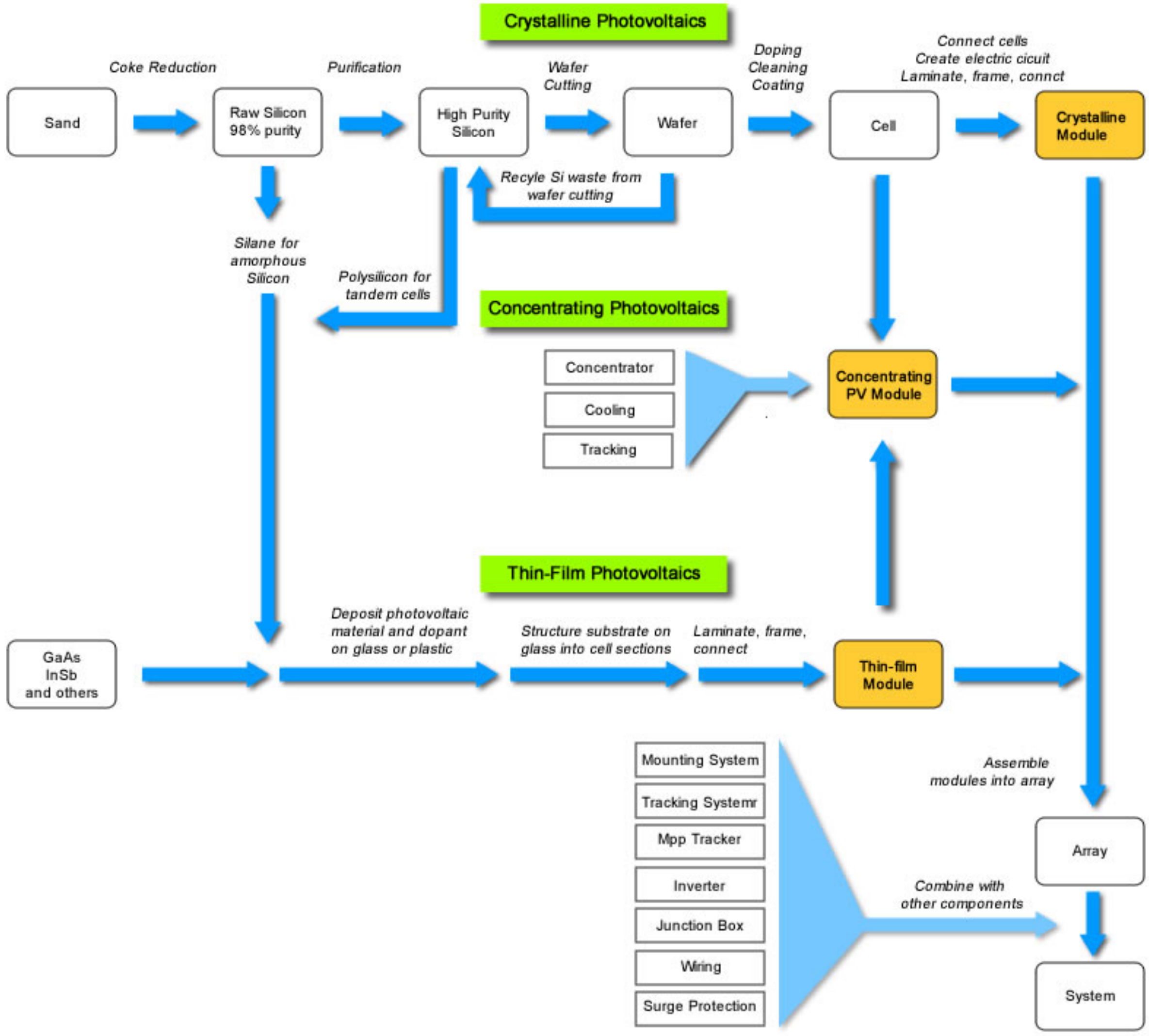

Figure II: The PV Value Chain

Source: Green Rhino Energy, 2013

4.2 The German PV industry background

The German solar industry has gone through rough ups and downs. Not so long ago, Germany was the leading country in the solar manufacturing industry. Installed capacity rose from just 2.9 GW (Gigawatt) in 2006 to 32.6 GW in 2012, of which the majority of production was manufactured in Germany. The leading firms in Germany were: SolarWorld, Q-Cells, Solan, Aleo Solar, Conenergy and others. These companies have dominated the German market and exported worldwide (Hockenos, 2013).

However, the situation has completely changed since the crisis in solar sector in Germany. Installed capacity rose from 32.6 GW in 2012 to only 41.55 GW in 2017, which is approximately 2.5 times slower growth than from 2006 to 2012 yearly growth (Fraunhofer ISE, 2017). The crisis was caused by lower government funding and competition from China. Chinese firms have overtaken and oversupplied the German domestic market with low priced solar production. In total, prices for solar modules have dropped around 80% (Fialka, 2016). Prices of PV modules have decreased from more than 4 USD per Wp in 2008 to less than 1 USD per Wp by January 2012. The decrease in governmental subsidies has also caused decreased overall demand in Germany as well. In general, the crisis came from two ways: increased competition and lower demand (Fialka, 2016).

Because of the crisis, not every company could keep up with reduction of costs and demand in Germany and those top companies that were once leading the world market before the crisis were overtaken by Chinese companies. For comparison, 120,000 people worked in German industry in 2011 and by the end of 2012 the number has fallen to 87,000. The same year, turnover fell dramatically from 11.9 billion euros to merely 7.34 billion euros (Hockenos, 2013).

Because of the increasing competition from China it was not possible to compete on price on generic product. Companies had to innovate in different ways to establish a competitive advantage by offering unique products for which customers would be willing to pay price premium (Porter, 1985). In this study, we have interviewed companies that have survived the crisis in order to investigate what kind of upgrading methods and mechanisms they have used in order to add value to their product and stay competitive in this highly competitive industry. A full list of participants in this study is available in Appendix 11.5 – Participants of the study and Appendix 11.7 - Overview of interviews and respondents.

5. Empirical findings

The empirical findings from the interviews with solar module manufacturing companies and research institutes are described in this chapter. The empirical data is structured into the five types of upgrading mechanisms with relevant subcategories.

5.1 Collaborations

5.1.1 Collaborations with universities and research institutes

Collaborations with research institutes and universities were common for the thin-film producers in the study. The thin-film producers argued that they to a large extent were reliant on these relationships, since they did not have all the capabilities in-house that universities and research institutes could offer, as explained below by Thin-Film-1 and Thin-Film-2

"I think it's very hard to research without a network of universities, because you don't have all the resources to do that ... We need to have the knowledge and the tools from the university" - Thin-film-1

"(...) they are equipped to do special things, which we are not able to do, like analysis, or process tests." - Thin-Film-2

Research-Institute-2 explained that the equipment that research institutes had were important for the thin-film companies to be able to test their innovations before making changes in their production line. To test something at the factory could mean that production was stopped for a day of trials, and if the trials were unsuccessful the company had missed one day of production. The research institutes thus gave the thin-film companies a way to try out new things without having to stop production.

Except for the equipment, which the universities and research institutes had, the people working there were also viewed as important for the companies. Thin-film-1 said that they tend to work with the same universities and institutes, because through having collaborations with known partners, the partners did not have to learn everything about their products and processes again and had knowledge into what Thin-film-1 was doing. Long-standing relationships were also specified by the other thin-film producers as important. According to Thin-film-2 other types of collaborations had ended during the crisis as companies went bankrupt, but universities and research institutes “do not disappear that often” and the company specific-knowledge is built up in people in the universities and research institutes which makes them very valuable for the companies. Thin-film-2 stated that if the people within the universities and research institutes disappear that is a problem for Thin-film-2, but also that they try to follow these people and collaborate with them in their new setting if they change workplace. Thin-film-1 and Thin-film-2 stated that universities’ and research institutes’ had specialists, which the companies themselves did not have, but needed, even if they did not have these collaborations. Through Government or EU funded projects companies were able to collaborate with these specialists without having to pay the actual cost of hiring them:

“And in a way, this is a financial support, because if we would have to hire all these people ourselves, we would need more specialists here, which we have to afford, and also if we have cooperation, then we are able to get state grants. [...] So, it also has a financial aspect beside technology input that we receive from these institutes.” - Thin-film-2

Furthermore, Thin-film-4 would also likely be very negatively affected if the research institute that they were collaborating with would disappear, as they said they were very reliant on this exclusive partnership. According to Thin-film-4, the partnership worked in a way where Thin-film-4 brought the *“technological achievements in the laboratory”* from the institute and implemented it in their large-scale production line. In a few years, they had brought up their module efficiencies from 11 to 16 percent and more, while breaking the world record, and this was, according to Thin-film-4, the achievement of the collaboration. Other thin-film firms in the study had also held the world record previously. To hold the world record in efficiency was expressed by the respondents as not as important as being able to have low manufacturing costs and rapid technology implementation into manufacturing lines. The leading thin-film solar module manufacturing companies are having quite similar module efficiency levels and Thin-film-1 expressed competing for the world record as a friendly, “healthy race”, which had more to do with showing the investors and customers where the technology could go, rather than “winning the race”. Research-Institute-2 described that this development evolved from the collaborations that the thin-film companies had with the institutes:

"Efficiency went up, I think we contributed significantly, but of course, apparently all very good institutions and their industry partners roughly ended up on the same level of technology…" - Research-Institute-2

Thin-film-1 noted that there were two main things that were achieved through these collaborations: efficiency increases and improvement of understanding the thin-film technology. Thin-film-1 said that compared to crystalline silicon, thin-film is a much more complicated technology, and they need to understand their device and the process. The universities and institutes could provide support through, for example, device simulation, micro analysis and new materials testing. Moreover, Thin-film-2 stated that to develop the technology, collaborations with universities and institutes were the most important as it allowed the companies to achieve fast innovation cycles.

To have the highest efficiency modules was not expressed by the crystalline silicon module manufacturers to be a way that they could set themselves apart from their competitors and no one brought it up as important. Compared to the thin-film companies, they are not responsible for the production of the cells themselves, which is the key input of increasing efficiency in crystalline silicon modules. The crystalline silicon module producers instead saw the international market as a mean to get the highest efficiency products, with China and Taiwan mentioned several times as leading the production in high-efficiency crystalline silicon cells, as explained here by Research-Institute-2:

"Chinese now have a huge manufacturing experience on wafer based solar cell production, so you have many technologists, who are as good or better than the people here or in USA or Japan…" - Research-Institute-2

The crystalline silicon module manufacturers in the study had currently no formal collaborations with universities or institutes. According to many of the respondents, collaborations would take too much time from them and some did not feel the need to invest both money and time into research projects. Of the niche market companies, a few stated that there was no interest from the companies themselves and often not from the universities or research institutes neither to engage in partnerships. These relationships were thus not deemed vital for the crystalline silicon module manufacturers.

"*It is our own decision, because it also takes time to manage all these parties together and the most of the time there is a problem with technology or maybe they are too busy, so (...) we are more into going with only ourselves" - Crystalline-Silicon-5*

The formal relationships that the crystalline silicon companies had, in general, were arms-length relationships, as supplier and customer. The crystalline silicon module manufacturers used the institutes for testing and receiving certificates. However, all companies, except Crystalline-Silicon-4, said that they had some informal relationships with the institutes where they discussed, among other things, market developments. For this, the companies usually had an experienced employee working and travelling to different events, representing the company.

"We have one employee. [...] He travels to them [research institutes] and talks to them. He gives his input, his knowledge, but there are a lot of people from other companies, the institute by itself and we try to find solutions. This is kind of our partnership. We give our knowledge to them, they give their knowledge to us and we work together. This is the kind of relationship we have with some institutes. […] It is important because you learn something about the development in the future. And you learn something about the competitors, you learn about new technology. Maybe technology you can use in the future or you learn something about trends." - Crystalline-Silicon-1

5.1.2 Collaborations with equipment manufacturers, material suppliers and installers

While formal collaboration with universities and research institutes were exclusively pursued by the thin-film companies, both thin-film and crystalline silicon producers discussed the importance of having close relationships with the equipment manufacturers and material suppliers to develop the machines, processes and products. The answers from Thin-film-1's and Crystalline-Silicon-2's representatives illustrate this:

"*Well, I mean, usually for CIGS (Copper Indium Gallium Selenide, a thin-film technology) the core technologies are custom build machines… So, there is a very close relationship between equipment supplier and the module manufacturer, because they need to learn how to* *build the machine and they need to get our feedback, so that immediately becomes a close relationship*" - *Thin-film-1*

"So, we have basically a very close relationship with the machine vendor, which is called (machine vendor's name). That is very important to us, because they help us to develop the machines to the next level." - Crystalline-Silicon-2

However, collaborations with equipment producers were only mentioned in three interviews (Thin-film-1, Thin-film-3 and Crystalline-Silicon-2). The possible collaborations with equipment producers were limited, as thin-film producers had become equipment producers themselves. Moreover, two of the crystalline silicon module manufacturers had developed a large part of their equipment themselves. The only company that spoke explicitly about what kind of collaboration it had with an equipment producer was Crystalline-Silicon-2. This was not only a collaboration to develop the machines, but also to develop next generation cells. Together with their machine vendor they were involved in an EU project, which was expected to continue from 4 to 5 years, as they developed new cell technology.

Good material suppliers were seen as vital for the companies, however, most of the companies did not discuss material suppliers in terms of collaborations, rather as regular customer-supplier relationships. The thin-film producers discussed the importance of having good glass suppliers, while the crystalline silicon producers specifically mentioned the cell producers. Both materials were seen as crucial in the development of the respective technologies' modules. Other materials, such as junction-boxes and cables from reliable suppliers, were also discussed as important to create a high-quality product. The materials from the suppliers were not only viewed in terms of performance of the modules, but also in terms of the durability as the module manufacturers had warranty programs extending for several decades. This meant that choosing the right suppliers were very important for the module manufacturers, as the quote from Thin-film-1 below illuminates:

"We need to have the knowledge and the tools from the university, but, of course, on the other hand, a bad material supplier can kill you" - Thin-film-1

Some of the companies also stated that they have developed synergies with installers and component suppliers for energy systems, for example:

"We learn and installers and system producers learn. They improve their technology and we improve our technology. Our technology is from year to year better and the technology from the inverters and the storage systems, and the combination of both." - Crystalline-Silicon-1

5.1.3 Collaborations through associations and networks

The thin-film module producers in the study also collaborated within interest organisations and organised yearly conventions where the thin-film module manufacturers got together and discussed market developments and special topics in workshops. As thin-film modules have a low market share, compared to crystalline silicon, these cooperations were viewed not only as important to learn from each other, but also to challenge the strong position of crystalline silicon both through technological improvements and through joint lobbying. A lot of knowledge was shared through these collaboration, which "*aligned*" the companies better, except the most "*core secrets*", according to Thin-film-3. This was further elaborated by Thin-film-2:

"*There is a special association for all the thin film PV companies, European association, but it is also very important for us. And that is the special thin-film topics are discussed together and also that we have stronger position then as all thin film companies together*." - *Thin-film-2*

The CIGS module manufacturers in the study had together with several other CIGS module manufacturers and research institutes contributed to a *white paper* to showcase the advantages and unique selling points of the CIGS technology. The thin-film producers did not only have collaborations through organisations. Sometimes they worked directly with competitors according to Thin-film-1 and Thin-film-2:

"Yeah, we work together also on specific topics. and that's…, for example, in this Thin-film organisation, now on the European level, where we are working on a study on the environmental impact of PV in general. [...] So, there is a … cooperations as well. Let's say we are competitors, but we are friendly with each other." Thin-film-2

"(We work with) sometimes even with competitors, so other CIGS companies." - Thin-film-1

5.2 Monitoring

5.2.1 Monitoring competitors

Crystalline-Silicon-2, Crystalline-Silicon-5, Thin-film-2, Research-Institute-1 and Research-Institute-2 stated that it is important to have employees who are responsible to follow symposiums, innovation think tanks and who are responsible to bring new ideas to the company, relating to R&D, design and other product features. Thin-film-3 added that it is essential to have good networking and to be informed of what kind of developments other competitors are doing. A response from Crystalline-Silicon-1 illustrates the importance of monitoring competitors:

"We know other companies, we know other suppliers, we know everybody in the market, but we have no strong relationships to them. We know them, because it is important to work successfully in the market, but not more. [...] It is important, because you learn something about the development in the future. And you learn something about the competitors, you learn about new technology. Maybe technology you can use in the future or you learn something about trends. Or what the customer is liking to have. So, it is important, yes." - Crystalline-Silicon-1

According to Research-Institute-2, Crystalline-Silicon-2 and Crystalline-Silicon-5, it is essential to always look at the competitors and analyse the latest state of the art technology. It does not require to spend a lot of money, it requires time and energy to attend different conferences in order to follow the latest developments in different technology fields. These employees are referred as "technology scouts", who are following market developments, monitoring what competitors are doing, what kind of patents are published and following news on the latest technological developments. Two quotes from Crystalline-Silicon-2 and Crystalline-Silicon-5 highlight this:

"We have employees, who are constantly in symposiums and following basically the innovation think tanks, and bringing in new ideas… and then these employees discuss it with

the management and say: "Ok, do we follow up on that one, do we wait, do we do it now?" - Crystalline-Silicon-2

"We are closely following the technology about the new strengths like perc cell technology and other thin film cell technologies, and we are always keeping a close contact with these producers. [...] We are always on track with what is the state of the art, what is the current technology and we can apply very fast." - Crystalline-Silicon-5

According to Crystalline-Silicon-1, market observations not only gave better insights of what kind of product developments are needed, but it also provided understanding that the market is growing too fast and that companies should follow a more conservative growth strategy and be prepared for a "market bubble burst". Thus, after analysing the market, companies were not only better at developing products, but were also able to predict market developments, like a market crisis, and prepare for it.

"We saw some risks in the last years, so that was the reason for not growing too fast. So not to spend too much money, not to grow too big or to build too big or to invest in many machines. Only invest in one machine and not in 10 machines. To have a good expectation in the market or in the development in the market. Not to think that the market will develop very quickly or the growing goes on and goes on. So, we were a little more careful than our competitors. I think that is the reason for our success." - Crystalline-Silicon-2

5.2.2 Monitoring customers

5.2.2.1 Customer preferences

According to Thin-film-1 and Thin-film-2, changes in the design are followed by the customers' needs and by their wishes. It is important to keep track with the market developments in order to get inspiration for ideas from the customers.

"We have to keep track with the market development, and we get ideas also from our customers, with regard to innovation, what they need, what they see as a market development, and we try to follow up, of course, on that, and develop even better modules on a regular basis." - Thin-film-2

"For BIPV (Building Integrated Photovoltaics), we learn a lot from the customers, because they, the customers, have their wishes, and their requirements. [...] You get feedback and you put a new feature maybe in your module… But also, sometimes more the semiconductor part comes out of R&D itself... So, no customer tells you how to make a semiconductor, this comes from original or real inherent R&D part, to optimise the semiconductor." - Thin-film-1

As stated by Thin-film-1, customer monitoring usually provided general information for companies regarding general design and product functionality. Customer monitoring and market research allowed companies to create products that were valued higher by the customers in the market, but did little for the technical performance of the module.

German quality, durability and engineering are world renowned, according to the respondents. Thus, most of the companies labels their products as "Made in Germany", in order to portray higher value image for their customers. Most of the participants stressed the importance of being a German manufacturer, because of the better image in the eyes of the customer as compared to products from Asia, which were viewed in the market as lower quality in general. Some of the companies are also trying to maintain environmental friendly products and image by reducing carbon footprint and provide the statistics to the customers. According to the respondents, this, for example, helped to win certain tenders where low product carbon footprint was one of the criteria. A response from Crystalline-Silicon-4 describes market monitoring and highlights why it is important to create high quality product image for the customer:

"...so, when you sell to a customer, which buys normally products with a real value, so then it's a person who have learned in his life to feel what kind of fabrics he bought, what kind of stuff he bought, if it's the plastic material with a value, or it's cheap rubbish. So, that's what I mean, the feeling of the product must also be comparable, and this is what also on ... a lot of Chinese product isn't. So, there are a few components assembled, but it's not a real design product, it is an assembly of materials, and that's in my opinion a point what Chinese haven't learned." - Crystalline-Silicon-4

5.2.2.2 Monitoring to develop niche markets

All of the companies and research institutes stated that for the German solar module producers it is not possible to compete on price on standardised products. Crystalline-Silicon-2 is one example, stating: the future is *"...not on standard products, you have to be different, and there will also be a certain market, where people appreciate local production…".* All the other interviewed companies and institutes held similar views. The manufacturing of "standard products", in this case modules competing on the international market on a price basis was seen to have been lost to the Asian industry. According to the informants, the German companies that tried to compete on price when the price drop occurred in the market were destined to fail, and the companies that quickly realised that they could not compete on price in the international market had a better chance of surviving.

"... every Chinese supplier is delivering modules below the minimum import price. So, from the very beginning for us it was clear that we have to be different from other companies (...) The ones that went insolvent were the ones, which tried to compete with Asia on the lowest price. And those ones that are still left are those that have unique selling point." - Crystalline-Silicon-2

According to the case study participants, in order to succeed companies have to increase the margins of their products, to make something new or to create new markets like BIPV. Module producers in Germany stated that competition in large volume projects brings very low profits and if unforeseen changes occur, like fluctuating foreign exchange rates, companies make no profit at all. It was therefore very little interest of the companies to compete on the main market. Respondents that survived the crisis explained the importance of finding a niche market or creating your own niche, creating special products with larger margins. Moreover, the majority of companies stated that flexibility, differentiation and innovation are the main reasons they have survived.

"It is really hard to compete in the market with the standard modules, because it is already there and the prices are getting lower and lower, and it is really hard to compete with China. So, we created our own "Blue Ocean" for this. These niche applications bring us to this new 'Ocean', which we can sell easier and with higher margins." - Crystalline-Silicon-5

Through persistent and long-lasting market monitoring, companies were able to identify special needs of customers that competitors were unable to fulfill. Some of the solar module manufacturing companies in Germany stated that their success lied in working in a niche with much higher margins and much less competition compared to generic mass production. For example, Crystalline-Silicon-4 did not even feel the effect of the crisis, because of its established niche market. Most of the respondents, in general, see their future in the niche manufacturing, being innovative and creating unique products, which have lower production outputs. Most of the companies underlined that they did not wish and it is not possible to compete on a large scale and on price with the Chinese companies. According to the respondents, those companies that compete head-to-head with Asian manufacturers will not succeed, as described below by Crystalline-Silicon-4:

"If I would compete on price, I would be dead directly, so you cannot compete, and this you must know, in my opinion, you have to know it. It's impossible." - Crystalline-Silicon-4

Some companies that survived the crisis have developed special technologies that made their product unique in the market. For example, Crystalline-Silicon-5 has developed a special membrane module for flat roofs, which allowed them to reduce installation costs, prevent rooftop leakage and reduce top load. Crystalline-Silicon-4 has developed a special, small and flexible production line for maritime solar modules which are salt water resistant. Crystalline-Silicon-3 entered a special niche market of repairs and changed their production to flexible manufacturing in order to repair the modules that are already in the market as well as manufacture custom-built modules of other manufacturers that were no longer available on the market to customers. Most of the manufacturers went bankrupt in Germany and their customers could not get in touch with them for solar module maintenance. Crystalline-Silicon-3 saw this market niche and started providing maintenance and repair services for customers that were having solar systems of manufacturers that no longer existed.

Another clear example of a niche market is BIPV. The majority of thin-film module manufacturers are focusing on BIPV, because it is tied to the local market, where margins can be higher and local presence is needed, according to the respondents. The BIPV market segment has specific requirements and utilises a very complicated network with architects, builders and facade makers, which requires market monitoring. According to Thin-film-1 and

Thin-film-2, regional companies have, thus, an advantage of being close to the customer and being able to directly participate in this niche. A standard PV module customers can be very remote, however, for BIPV or other niche markets there always have to be an ongoing relationship, monitoring and learning interaction between customer and manufacturer, because customers have specific requirements and needs, which standard PV module customers do not have. Thin-film-1 has, for example, developed different kind of color spectrum for BIPV solution to make the modules more appealing for the end customer, architects and facade builders. The company also manufacture modules that have unified color throughout the frame and specific solutions for buildings.

"The module is completely black, there are no clamps, no frame, it is more suitable for BIPV" - Thin-film-1

5.2.2.3 Full solutions

Market monitoring allowed companies to investigate customer needs regarding functional upgrading. Majority of case respondents described that moving into new configurations across PV value chain to increase the value added is necessary for German module manufacturing firms. Thus, many of the companies went from selling modules to selling *full solutions*. The strategy of the firms was seen to bring more value to the customers, as the customers did not have to deal with several suppliers, but could buy everything from one vendor. Module manufacturers could also benefit through the possibility of increasing their margins and being more attractive to the customer, i.e. this was looked upon as a "win-win" situation.

"*Companies, who early understood that they had to sell solutions, energy solutions, these were the companies that had a good chance to survive" - Research-Institute-3*

One part of full solutions is to sell additional products, for example, inverters, mounting equipment and storage systems to the customers together with the solar module. This was viewed as a natural step in the development for the module manufacturers, as explained by Crystalline-Silicon-1:

"The focus goes more to sell the customers the whole solutions. That means, first, a module producer sells only modules and the second step was 'OK, the customers need more, they need inverters'. So, we need more solutions that makes it more comfortable for the customers, because there is only one building system with every equipment. It makes it for the customer easier [...] more turnover for us, more service for the customer and more success for the whole company." - Crystalline-Silicon-1

Selling custom solutions was seen as a way to differentiate against competitors, in general, and, as Crystalline-Silicon-1 mentioned, it was especially a way to differentiate against Chinese companies, because "*they do not offer the full service*". According to Crystalline-Silicon-1, this was a development that started several years ago, and because many other German firms offer full services, the customer expected it. If a company would not offer full services, then it would have a disadvantage on the market. A response from Thin-film-1's company representative illustrates well the opinion held by the majority of respondents:

"*I think when you look at other companies they only survive because they have much more than the module […] because that's how you can increase the value added*." - *Thin-film-1*

Crystalline-Silicon-1 also explicitly underlined the importance of offering full solutions to the customers by saying that it would be difficult for the company to compete against Chinese firms without the full solution offering. Another reason for selling full solutions, according to Thin-film-1, was that they also got more knowledge about their own products, i.e. better feedback from customers, which could be used to improve existing products. Companies that are offering full solutions usually target smaller customers. According to the respondents, larger customers are more interested in price to performance ratio. They are ordering different components from different suppliers and combine full solutions by themselves in order to reduce costs, while smaller customers are willing to spend more money in order to receive a product that has full functionality, saving time and energy by dealing with only one supplier.

In general, all of the respondents, including industry experts from research institutes, agreed that the future for German solar industry is offering full solutions to the end customer. Most of the case participants already follow this strategy and have close contact with their customers.

“We try to understand what is the problem of the customer, and we are trying to make solutions for that problem. That is also making us special in this way, I think. It is not just yeah ... ‘Buy the modules and go away.’ We get deeper into the problem and we get into close contact with customer. Even if it’s a small project we are in contact with them.” - *Crystalline-Silicon-5*

Most companies added the functional upgrading to their existing value chain activities, Crystalline-Silicon-3, however, can be seen as moving down the value chain, leaving the former activity of mass producing modules, and focusing on repairing and special manufacturing for customers’ broken modules. This move down the value chain meant that they no longer had to compete on the international market, but only on the local German market. Crystalline-Silicon-3 thus saw hundreds of competitors shrink to two-three companies that they viewed as competitors, by moving into a niche market.

Project planning was another service that companies offered. Project planning requires that you are able to communicate effectively between the parties. It involves calculating and providing the best solution for the customer in terms of price and quality ratio. In most cases, the respondents agreed that it is an activity that must be done locally.

“We are also doing some project design proposals for customers. Like such as, how much of energy they are going to generate in this location, and how much money that they are going to save over the years, and what is the overall investment is going to be. [...] Then we talk with them and then they do the project, and we supply solar modules, but of course we are helping from with the technical questions and taking a side of the project as well.” - *Crystalline-Silicon-5*

One German company that was mentioned in several interviews, which was not interviewed, was seen as somewhat of a pioneer in selling the whole systems. Selling of systems was seen as the competitive advantage of this company and the way that they were able to compete on the market successfully. Besides offering energy systems, this company also offers services, such as training, to their customers. Of the interviewed companies in this study, several also offered services to the customers. Some companies said they were offering training. This training helped the customer to understand and use the product in the right way.

5.3 Internal mechanisms

5.3.1 Experience and knowledgeable employees

Most of the companies that participated in the study signified the importance of having a long-lasting experience in solar module manufacturing in order to be successful. For some of the companies, especially operating in the thin-film sector, it can take a long time to develop products until the actual manufacturing starts:

"We needed a long time to develop these technologies, I mean, when we started, before we sold our first solar modules to the market it was four years. [...] A lot of companies tried, but [...] you need time to develop the right production process, and maybe it is looking easy from the outside, but doing that is not that easy. You need some time, you need some money, and you need support over the time." - Thin-film-2

The companies and research institutes discussed that most technologies are available to all companies within the industry. However, the difference, according to the respondents, resides in the way companies work with the knowledge that they have, which is related to company's long experience, illustrated here by Crystalline-Silicon-1:

"One point is the experience we have, more than 15 years experience. But we are not alone, so other companies have also a lot of experience in the market, but we saw in the last one or two years a lot of new competitors with not long experience (disappear). So I think that our experience is one part of our success." - Crystalline-Silicon-1

Thin-film-4 highlighted that the equipment by itself does not produce a module. Companies need, for example, knowledge in how the processes should be formed, which material and what composition of materials should be used, and what temperature should be used in the vacuum deposition process for thin-film modules. The age alone was thus not seen in isolation to the survival of the companies, the employees long-lasting experience in the field was viewed in conjunction with age as a reason for surviving. The majority of companies brought up the importance of having employees working in the company for many years and through this developing a lot of know-how. The employees were also seen as important for the development of relationships with the external environment. Personal contacts built up over the years tied the companies closer to other stakeholders in the PV industry, which is explained below by Thin-film-2:

"(...) most of the people, who are responsible for the departments' technology, engineering and so on, they have been here for a really long time, so they were able to build these close relationships and networks that we are focusing on, so we do not have too many fluctuations here also in Germany." - Thin-film-2

Crystalline-Silicon-5 held a similar view and said that if you would "rip out" all the people from the company and replace them with new people it would not work, not only from a technical point of view, but also because everyone in the company had a lot of contacts within the solar industry.

5.3.2 Manufacturing in Germany

During the interviews held with the company representatives, when asked: *"What is the main advantage for you to be located in Germany?"*, most of the companies immediately replied that the people who are working in the company are the main asset. According to the respondents, knowledge and experience resides in people and while you can move equipment you cannot easily transfer the people and knowledge and experiences that they have. Moving their activities abroad was thus not seen as a viable option for most of the companies in the study, as Crystalline-Silicon-1's and Crystalline-Silicon-2's answers exemplifies:

"... of course, there is a certain part that comes from the machine and the machine you can re-locate, but there is also a lot of human know-how inside and the people who are working in this company have experience for more than 25 years. So, yes, you can change it to any other place, but you lose a lot of know-how and that loss we wouldn't really do." - Crystalline-Silicon-2

"There is not a lot of difference in China or in Germany. The difference is in the way that you produce, the knowledge that you have, the experience you have. […] Employees who work more than ten years for us, [...] the worker on the machine (in our company), he knows how to produce good modules, he knows how to use the machine in the right way. To produce a

module it is not so difficult, but to produce a good module with a good stability and longer period. This is not so easy." - Crystalline-Silicon-1

Crystalline-Silicon-1 further stated that it might be cheaper for them to produce in another country, but it would be risky to try to move because of the knowledge that was built up in Germany. This was verified by other companies and research institutes. Research-Institute-2 stated that you would probably not get anything sensible out of shipping the equipment over to China and trying to assemble it, as machines only together with experienced people are able to produce high quality modules. Thin-film-2 argued that some companies had research labs in some part of the world and then produced in another part of the world, but Thin-film-2 saw this as difficulty. They needed close interaction between technology, engineering and production. The combination of these factors with experienced personnel in all departments of the company was hard to find in another location. Crystalline-Silicon-5, which had acquired a company in Germany, agreed that it was employees in all departments, who played a huge role in the location advantages in Germany. According to the Crystalline-Silicon-5 representative, even the machine operators were better in Germany compared to other parts of the world, much due to the educational system. Moreover, Crystalline-Silicon-5's representative stated that it is not enough to acquire just the patents and IP rights of the company to become successful. Scientists and key engineers are also important to secure that the know-how in the company would live on.

5.3.2 Creating and adapting the manufacturing equipment

According to most respondents, having long-lasting experience in the field and professional employees is one of the essential elements in order to be a successful solar module producer in Germany, as this experience enabled companies to create their own manufacturing equipment or adapt the standard equipment to specific manufacturing processes.

"The whole production line: stringing, the laser cutting of the cells and so on, it is every time we have done it completely by our own, because most times the solutions you find on the market are focused only on the real mass production. So, this is not suitable for us." - Crystalline-Silicon-4

In order to develop stronger competitive advantages some manufacturers manipulate their equipment quite dramatically. Competitors are able to buy the standard equipment in the market, however, some companies claimed that to be successful it was important for them to develop their own custom machines, as the competitors can not easily copy the software specifications, the hardware, the programs etc. Some module manufacturers, thus, try hard to protect the knowledge about their manufacturing process and maintain this as unique competitive advantage, as pointed out by the Crystalline-Silicon-2 company representative:

"On purpose we stop the warranty and service programme with the lender [equipment manufacturer], because we know that they would try to copy-paste and bring it to other (module manufacturers)." - Crystalline-Silicon-2

The competitive advantages stem from trade secrets and know-how for some companies. Today's solar industry, in general, is not technology driven, but driven by the ability to implement technology into the manufacturing process in an efficient manner, according to case study respondents. For example, Research-Institute-2 stated:

"Now it is more about speed. Of course, you want to keep you tricks and your know-how, but it's more essential to just bring up developments into the production line quickly and it is certainly not easy…" - Research-Institute-2

Since the technology is available to almost every company in the market, the competitive advantage is related to how fast companies are able to implement technology in their production and to keep the know-how within the companies, several respondents, including Research-Institute-3 and Crystalline-Silicon-2, stated:

"It is very difficult to protect your IP by patents today. I think it is really know-how and it is a constant stream of innovations that assures that you are a bit faster than your competitors." - Research-Institute-3

"This is why when they do a copy-paste of mine, I already have the next year generation here (...) So, you have to be faster than the rest, that is the key." - Crystalline-Silicon-2

5.3.3 Quality and durability

As module efficiencies were similar across manufacturers, quality and durability were also seen as ways to stand out on the market. According to several firms, quality and durability can only come from many years of experience and internal competences developed through learning by doing. Though firms, in many cases, can purchase the same equipment and input factors, it is the internal knowledge how to use the equipment and which input factors to acquire that determine the quality and durability of the product. As pointed out previously, just owning machines to be able to produce PV modules compared to owning the machines while also understanding and refining the processes are quite separate things. The remaining German module manufacturers have a long experience in the field and were viewed as having high quality and durability of their products, both stated by companies and institutes in the study. To produce in Germany was thus a way to increase the symbolic knowledge of the company, as the quote from Crystalline-Silicon-2 shows:

"The "Made in Germany" is still a proof of quality and for premium. And that is why for us it is part of the marketing story." - Crystalline-Silicon-2

Crystalline-Silicon-4 also highlighted the value of being active in the industry for a long time - to understand what works and what does not work. The company is working in the niche of selling modules for boats. Over the decades they have seen many companies entering and exiting the market and most of them only lasted a few years, according to Crystalline-Silicon-4. Not having the experience of manufacturing modules for seawater conditions, meant that other companies did not realise, for example, the importance of a completely water tight cable outlet, which meant that the modules did not sustain for very long. Moreover, according to Crystalline-Silicon-4, many new companies tried the same solutions as companies before them, thinking that they were the first company to ever do it, coming up with the same negative results as the ones before them. Crystalline-Silicon-2 also highlighted that they, through years of experience, had low breakage and scrappage in their production process, compared to competitors, and this meant that they could keep down costs and create a higher quality and more durable product.

5.4 Mobility

The case study participants stated that it is important to develop internal capabilities within the company, rather than discussing the importance of employee mobility. Overall employee mobility was not stated as important mechanism for upgrading in order to survive in the German PV module manufacturing industry. In the analysis part we provide a discussion based on the answers by the respondents and relate it to theory to why mobility was not mentioned as an important factor for companies' survival.

5.5 Acquiring

5.5.1 Acquiring equipment

As mentioned before, most of the companies stressed the importance of having high quality and reliable products. Crystalline-Silicon-1, Crystalline-Silicon-2 and Crystalline-Silicon-5 stated that knowledge and competitive advantage is related to the purchase of the latest state of the art equipment, producers have to invest into the latest equipment in order to maintain leading positions and high-quality standards in the market. For example, one of the companies stated:

"We modernise the equipment, the machines, every year, or every two years, three years. Because the technology will change a little bit, the busbar will change, the cells will change. So, we need new equipment to produce the new raw material. [...] And our production lines are state of the art. That means we invest a lot of money in our production lines. They are very new or brand new. Last year we invested a few million euros in new stringers. That means we are state of the art." - Crystalline-Silicon-1

However, because the general conception was that everyone had access to the same standard equipment, the competitive advantage did not lie in just buying the machines, but how they were used as explained in chapter 5.3 *Internal Mechanisms*.

5.5.2 Acquiring other companies

Thin-film-4 was the only German company in the sample which had acquired another company. By acquiring another company, Thin-film-4 was able to upgrade the module manufacturing to producing CIGS turnkey production lines. The reason for Thin-film-4 acquisition of the other company was clear from the start:

"... we did not buy [company name] because we wanted to become a module manufacturer, instead actually we wanted to strengthen our product portfolio by also offering a CIGS turnkey production line to potential module manufacturers" - Thin-film-4

The other thin-film companies in the study had followed similar paths, but instead of acquiring other companies, they had been acquired by other, foreign, companies. Thin-film-1 and Thin-film-3 have started developing production lines for other solar module manufacturers after being acquired. Both companies went insolvent during the crisis and were acquired by Chinese companies. The companies' roles have become to transfer technology to their mother companies, so the mother companies can build up production sites, firstly in China, then likely in other countries as well. The focus has thus changed from producing modules to R&D and developing CIGS production lines. Thin-film-3 has sold one FAB (Fully integrated production line) to China and is in the final negotiations about another two, while Thin-film-1 owner is looking to set up production sites in China. It is important to stress that before being acquired these companies operated only in solar module manufacturing field. A response from company *Thin-film-1* illustrates the change:

"Sure, we have now a different role. We are a producer, but we are also technology provider, I mean, it's very clear we were bought, because we have the technology and we are advising and practically working in transferring this technology to China and all over the world for [company name]." - Thin-film-1

The focus after acquisitions shifted to selling FABS for these companies, however, they are all still producing modules in Germany, but to a limited extent. The production in Germany is used by these companies for testing the equipment, rather than mass production, with all of them seeing BIPV as a future potential market for their module production in Germany.

"Even though producing modules was not the target, but, of course, in the end they fall out, in the end of the line. And then you have two possibilities: you can either throw them away, or you use them for BIPV projects in this case." - Thin-film-4

Most companies in the study, which acquired or were acquired by other firms, combined their knowledge bases with the other company and adapted their activities in order to develop a better competitive advantage. Responses from Thin-film-2, Thin-film-4 and Crystalline-Silicon-5, illustrate examples of all companies regarding knowledge development through acquiring. Thin-film-2 stated that after being acquired, the company was able to benefit from support for developing production processes from the mother company:

"Some of our shareholders also operationally support us, they come here and look at the processes, they walk with the people through the production line and look at everything, because they got a lot of experience in the glass and coating industry. So, they really can support us, not only by funding the company, but also by valuable input they are giving to improve the development of the company." - Thin-film-2

Thin-film-4 also explained how combination of knowledge and technology led to a better outcome after a Chinese company acquired a minor share in Thin-film-4 and they started to cooperate and combine their knowledge:

"Yes, so they do similar things as we do in our innovation line, but now we bundle their knowledge and our knowledge and we want to build another innovation line in China together. So, like the one we are running here in Germany, we want to set one up in China" - Thin-film-4

Thin-film-1 and Thin-film-3 also received help from their mother companies, after being acquired, to enter the Chinese market. Thin-film-3 was training teams in China to be able to talk to the Chinese customers, because it is hard getting a foothold in the Chinese market, according to Thin-film-3, since many Chinese do not speak English. Thin-film-1 owner has recently formed an EPC (Engineering, procurement, and construction) company that has minor operations in China and Germany, developing PV power plants. By being acquired the companies were, thus, able to enter markets, which were difficult to enter before.

6. Analysis

This chapter analyses and explains the empirical material by applying the theory found in the theoretical framework. First, the dominant design framework is used to analyse the empirical findings to give the reader an understanding of the technological context in which the firms operate. Then the data is analysed through the five upgrading mechanism compiled by the authors. The chapter ends with a table, summarising the most important relationships between the types of upgrading, upgrading mechanisms and knowledge bases.

6.1 Module manufacturing industry analysis

The first and second-generation cell technologies (crystalline silicon and thin-film respectively) utilised by the firms in this study have made marginal progress in record cell efficiency during the 21st century (see Appendix 11.6 - Best research-cell efficiencies) and both have a theoretical limit of around 30-35 percent efficiency (Rühle, 2016). As technologies are getting closer to their physical limit, the effort in development compared to the performance gains diminishes (Foster, 1986). This is likely why the empirical evidence suggests a resistance of companies to invest heavily in technology innovation. The research also suggest that many companies possess similar technologies and product efficiencies, a hallmark for the later stages of the dominant design framework, and where quality-to-cost is the main source of competition rather than product performance (Utterback, 1994). Becoming the "*innovation leader means to spend money, money, money*" as Crystalline-Silicon-1 put it, and might, thus, negatively affect the quality-to-cost ratio.

The result suggests that process innovation has become more important for companies than product innovation for survival, as the Dominant Design framework suggest in the later stages of technological innovation (Utterback, 1994). However, there is a clear difference between crystalline silicon and thin-film. Thin-film producers stated that they are still innovative through research projects with institutes and universities, because their technology is not yet as fully standardised and developed as crystalline silicon. This is supported by Rühle's (2016) findings, that crystalline silicon is closer to its physical limit. Moreover, looking at the manufacturing process of thin-film and crystalline technologies, one can notice that the thin-film module manufacturing process is much more complicated. Crystalline silicon producers are ordering the already made cell and combine it in the module, however, thin-film producers have to combine different materials by themselves and produce the cell on the glass or plastic by themselves (see *Figure II*, page 30). The thin-film firms stated that technology variations between different companies existed, and thus firms needed analytical knowledge to be developed. The results therefore suggest that the thin-film technologies are more in a *transitional phase,* according to the dominant design framework, while the crystalline silicon technology has reached the *specific phase*. In the *transitional phase* process innovation has exceeded production innovation in terms of importance, however, they are both relatively important (Utterback, 1994). As found in the study, the thin-film module producers did utilise more analytical knowledge in their innovation process.

Despite the differences in which phase the technologies were in, all parties downplayed the role of technological superiority as key to be able to compete in the market. This might be due to several reasons. First, as already mentioned, in mature technologies the benefit of increased research effort decreases as the technology closes in on its physical limit (Foster, 1986). Second, the result of this study suggests a business landscape of *weak regimes of appropriability* (Teece, 1988), where codified knowledge is hard to protect through patents and easily imitable. Patents did appear to play a minor role in the competitive advantage of the German firms, according to the findings. The problem of protecting patents meant that a sustained competitive advantage from patenting technology was not seen as viable and the codifiable nature of analytical knowledge (Asheim et al., 2007) meant that many companies in the industry more or less had the same analytical knowledge available as explained by several institutes and companies when they argued that competitive advantage lied in the speed of implementation, rather than a sustained advantage from the technology itself. Third, the codified knowledge was readily available by the close connections of the different actors within the industry, which made news of technological developments in the sector travel rapidly.

6.2 Collaborations

Though companies and institutes alike agreed that the linkages between module manufacturers and the rest of the innovation system had weakened, following the crisis and the subsequent bankruptcy of many firms, there were still collaborations, mostly between the firms in this study which relied more on technology as a mean to compete against other actors. This is in line with Lundvall (2010), which state that learning by interacting is more vital where technology is developing and more complex. The importance of collaborations differed significantly, depending if the company utilised crystalline silicon or thin-film technology. Crystalline silicon module producers had overall less collaborations with the external environment and some had no collaborations at all, which they felt brought value to their business. The empirical findings suggest the importance of analytical knowledge for the firm as a key determinant of collaborations with universities and institutes. Due to the earlier stage characteristics of the Dominant Design framework, e.g. differentiating production processes, (Utterback, 1994) found among the thin-film producers, and that they claimed not to have all the capabilities which could be provided by universities and research institutes, it was not surprising that they were collaborating frequently with universities and research institutes. German universities and research institutes, thus acted as an extension of the companies' own R&D department. Collaborations can lead to learning and new technology creation or modification of existing technology (Lundvall, 2010). Thin-film-4, for example, stated that the collaborations they had with a research institute was the reason they were able to bring up cell efficiency to record-breaking levels. Thus, collaborations with research institutes and universities appear to have played a significant role in the survival of the thin-film module producers by positively affecting their analytical knowledge base and through this product and process upgrading.

The thin-film module manufacturers were also collaborating frequently amongst each other within networks and organisations, where they shared knowledge and their latest development, but not in terms of their most valuable trade secrets. The empirical evidence thus suggests that informal collaborations, in this case between competitors, are important for product upgrading through aligning the competitors' technological know-how with each other and through this making faster technological advancements in challenging crystalline silicon's dominant position in the market.

Collaborations with suppliers were, however, important for both crystalline silicon and thin-film module producers. By collaborating with suppliers, firms could increase their synthetic knowledge base. According to the dominant design model, process innovation becomes more important for firms than product innovation after the early phase of innovation, and innovation often comes from suppliers in the later phases (Utterback, 1994). It is thus not surprising that several respondents talked about the value of relationships with machine and equipment suppliers in order to process upgrade, i.e. improving the efficiency of the production process. By having close cooperations with machine and equipment producers, module manufacturers could thus increase their output capacity. However, many of the module manufacturers had become equipment manufacturers themselves, and as such were less dependent on external manufacturers. As the prices of modules have dropped, a good way to decrease costs per unit was to bring efficiency up. As explained before, the physical limit of the technologies used by the companies are getting close, but the speed of production can be increased significantly, not the least showed by Crystalline-Silicon-1, which had increased their production capacity manifold during the 2010's, largely due to incorporating new equipment and processes. To have good material suppliers was deemed as vital for the survival of the module manufacturers, however, only one company stated explicitly that they had innovative collaborations with a material supplier, which could lead to product upgrading in a future perspective, through new cell technology. The importance of these relationships appears rather low and this suggests that collaborations with material suppliers were not essential for the survival of German module manufacturing firms.

6.3 Monitoring

In accordance with the study of van Tuijl et al. (2016), monitoring was found to be an important mechanism to develop a symbolic knowledge base. The module manufacturers studied their external environment to recognise where the market was heading and what their customers were demanding.

In terms of functional upgrading as well as product upgrading, customer monitoring was found to positively affect the symbolic knowledge base. By offering, for example, training for the installers the firms could discuss the market more deeply and understand the needs of their customers. The importance of local presence for symbolic knowledge creation (Asheim et al., 2007) was thus an advantage for German producers on the regional market. Monitoring customers spurred innovation and it allowed for the development of specific solutions, which fit customers' needs. Service offerings were found to be important to all companies, however, it might have been most important to Crystalline-Silicon-1, since they competed in the crystalline silicon standard module market, and thus faced intense competition from low-cost competitors.

By maintaining a close eye over the market and end customer, companies realised that the customer, in general, not only needs solar modules, but electricity and full energy solutions. The case participants uniformly agreed on the importance of *functional upgrading* by providing full energy solutions in order to survive in the competitive market. Value-added services create competitive advantages over foreign firms, because it usually has to be local and requires adaptations and flexibility in different cases, as stated by the company representatives. According to the findings, larger customers, e.g. solar park developers, have experienced engineers, who are able to investigate and purchase modules, inverters, batteries, etc. by themselves from different suppliers to the lowest cost and are thus not interested in full solutions. These customers are, however, not the target customers of the German module manufacturers, since price is a determining factor to win these tenders. German firms' main target market, small or medium sized customers are, however, more willing to pay price premium in order to receive reliable solution from one supplier, saving time and energy. The findings suggest that those manufacturers that monitored the market and were able to realise this were able to increase their competitive advantage on the regional market vis-à-vis foreign firms by offering full solutions and were able to increase the symbolic value of their product offering and thus increased their chances of survival. In turn, the companies which did not offer full solutions were more at risk to be compared on a price-to-price basis against foreign firms, which would not be favourable to the German firms (Schachinger, 2016). As a cost leadership strategy usually allows only one cost leader (Porter, 1985), offering the modules as part of the package was thus a way to avoid a "race to the bottom", which according to the respondents, some German companies engaged in, leading to the detriment of these companies.

Another way to avoid direct price competition with international manufacturers is to target niche markets (Humphrey & Schmitz, 2002). This, according to the respondents, allowed to a larger extent increased profit margins, since there is less focus on economies of scale in niche markets (Teece, 1988) and less competition. However, niche markets also limit the possible company revenues, because of their smaller size. No company in the study expressed a keen interest to compete in the regular module market against tough international, especially Asian, competition on price. In fact, most of the niche companies stated that they were quite satisfied competing in the niche markets, even with limited growth potential. Companies like Crystalline-Silicon-4 and Crystalline-Silicon-2, even proclaimed that they did not wish to become larger companies. These companies stated that they are able to generate higher profits with smaller scale production and having full production with existing capacities was enough for these companies. Moreover, Crystalline-Silicon-4 even stated that the company experienced no effects of the industrial crisis, because its niche is isolated with protection barriers from others (Humphrey & Schmitz, 2002).

Niche markets are about understanding the needs of a particular customer on the market. The results suggest that monitoring the market is an important mechanism to understand the customers' needs together with informal relationships. For example, Crystalline-Silicon-4's solar modules are adapted for maritime conditions and are salt water resistant. These kinds of solutions require special know-how, product adaptations and special solutions, which usually come from informal relationships with the customer and market monitoring. Crystalline-Silicon-5 is another example; the company has developed special panels, which can be integrated into rooftop membrane. The majority of other companies have entered the BIPV niche market with special mounting, design and installation solutions for buildings. The results suggest that for foreign companies it is much harder to compete in local niche markets, because it requires being present, close to the customer and having a good understanding of the market. For example, all of the case participants stated that the BIPV market is always going to be local. This relates to the synthetic knowledge base, which includes innovation through applying or combining existing knowledge (Asheim et al., 2007). Personal face-to-face interaction in this case is very important, because of the tacitness of the know-how and the custom solutions. Interaction between, and input from, users and producers is crucial as the process is many times of a trial-and-error variation, which calls for closeness (Thomke, 2003).

6.4 Internal mechanisms

The informants in the study uniformly stated their employees being one of their greatest assets and a main reason why they were still producing in Germany. This also strongly suggests the significance of synthetic knowledge within the German firms, because of the tacit nature of it (Johnson et al., 2002). If all knowledge was codifiable, there might have been less reasons to keep producing modules in Germany. However, many firms stated that a combination of analytical and synthetic knowledge was important to them as well. According to Johnson et al. (2002), analytical and synthetic knowledge bases should be seen as complements to each other, since codified analytical knowledge is only valuable if it can be decoded and interpreted, which needs synthetic knowledge. The experience and the formal education of employees was thus important for the companies to fully utilise the know-how within the companies.

According to many of the firms and institutes, and in line with theory which states that repetition leads to improvements in process efficiency and product design and performance (Pan & Li, 2016), experience was directly linked to the quality and durability of the products. Since German firms were unable to compete on price, quality and durability was seen as a way to differentiate themselves against the low-price alternatives. Incremental process upgrading, which is viewed as important in upgrading theory to increase performance (Humphrey & Schmitz 2002), was seen as the only way to achieve quality and durability and internal expertise through years of know-how facilitated it.

For example, as machines were mainly bought in from the large equipment producers, which other firms on the international market also had access to, the competitive advantage did not stem from what kind of machines were used, rather from how the machines were used. Some companies had, however, gone further and adapted and calibrated the machines to their production process and some had even developed some machines on their own. According to Teece (1988), trade secrets can be utilised by companies in industries where innovation comes from processes. As process upgrading had become very important for companies, some went to great lengths to keep the processes secret, as the trade secrets enabled them to compete on the market and ultimately survive. The results suggest that trade secrets were mainly based on know-how, i.e. tacit knowledge, which is easier to keep secret than codified knowledge (Teece, 1988). The overall picture given by the respondents was thus that everyone with the financial means could buy the equipment and produce modules, but to produce high quality modules many years of internal know-how was needed, which the German firms had, and used every mean to keep secret. “Made in Germany” was agreed by the respondents to represent quality to the customer. As such, producing in Germany increased the firms’ symbolic knowledge base.

6.5 Mobility

None of the respondents stated labour mobility as being important for their survival and the empirical findings suggest that mobility seemed of minor importance to the module manufacturers. In fact, the opposite, immobility in many cases seemed to be of greater importance. Gordon and Molho (1995) and Eriksson et al. (2008) have showed that employees with a long presence in a region and a particular company are less likely to change jobs. Fischer et al. (1998) points out that the propensity to move decreases the longer a person stays within a company. One reason for this is that employees establish relationships with, for example, colleagues and clients and these relationships might be significantly affected by a job transfer (Fischer et al., 1998). As described previously, many companies talked about employees working in the companies for many years as part of their competitive advantage. As close relationships between the company and employees built up over time, it had negative effect on mobility of the employees. Employees are thus tied to specific project or specific location and can be viewed as sunk cost in case of company migration (Fischer et al., 1998). That is probably also the reason why most of the companies stated that they are not considering to move away from Germany, because they do not want to lose employees, who are knowledgeable in specific technology, have specific skills or competences. The specialisation of many companies in the study, especially, the niche companies, and the importance of tacit knowledge and an incremental development process signals that place-specific human capital was an important factor in many companies, and the reason for firms keeping their employees was thus strong. Bringing new employees into the firm with possibly unrelated competences would possibly have a negative impact on the company (Boschma et al., 2009).

Furthermore, the thin-film module manufacturers in the study cooperated extensively, according to the respondents. Because of this cooperation knowledge was distributed through these networks to “align” the knowledge between the companies and, as such, the inter-firm labour mobility is likely of less importance for survival of the firms. The cooperations possibly meant that employees of these companies had similar competences, which in turn would not lead to increased productivity because of inter-firm labour mobility (Boschma et al., 2009).

In global value chain studies, mobility has been viewed as an important factor for upgrading in developing countries' firms, with workforce from or trained in developed countries (van Tuijl et al., 2016). Since Germany had one of the longest experiences in the PV industry, the knowledge flow from the outside was probably of lesser importance and the empirical results suggest that the knowledge flows went out rather than in, mainly through the Chinese establishment in the country. The thin-film module manufacturing companies, which were working as R&D centers for Chinese mother companies, are good examples of this. This finding is supported by a study of De La Tour et al. (2011) which stress that mobility of a skilled workforce was a key factor for the development of technology and manufacturing processes in the Chinese PV industry. Chinese PV companies benefited a lot from highly skilled employees, who brought professional networks, capital, and technology gathered in foreign firms and universities (De La Tour et al., 2011)

6.6 Acquiring

Qiu et al. (2013) found that technology transfer through acquisition was of great importance for Chinese wind turbine firms to upgrade their capabilities. This study shows that upgrading through *acquiring* was of minor importance for the German PV manufacturers and seemed to be of greater importance to developing countries' firms in order to compete in the market. Only one German company in the sample, Thin-film-4, had made a larger acquisition of another company. Through this acquisition Thin-film-4 was able to gain exclusive access to a research institute's research as well as form an exclusive partnership with them. This falls in line with Granstrand & Sjolander (1990) research where the authors describe knowledge development through acquisition. Acquiring other firms was, however, important for Chinese firms which had become owners or partial owners of almost all German thin-film firms in this study. The Chinese owned firms all stated that their main role now was to transfer technology to the mother company, and their tasks was to act as R&D centres and developers of production lines. This is similar to Thin-film-4, which stated that the purpose to acquire another company was to build production lines and develop better knowledge and competences through module manufacturing. This suggests that module manufacturing companies were acquired not for the module manufacturing purposes mainly, but for more of R&D and technology development purposes. Following the reasoning of Granstrand et al. (1992) and Humphrey & Schmitz (2002), the incremental upgrading of years of experience of these companies led to the firms' being able to take on more complicated activities. The empirical findings suggest that thin-film companies were acquired because of the technological knowledge and capabilities that they were able to create through many years of experience and technology development. Thus, German thin-film module manufacturing companies probably survived the crisis and were acquired, because of their developed knowledge bases and technology. The thin-film firms' increased skill content of their activities and the subsequent *chain upgrading* was thus important in order to survive.

Through acquiring other firms, companies can gain analytical, synthetic and symbolic knowledge, the research shows. For example, Thin-film-4, through its acquisition gained access to analytical knowledge in the form of an exclusive partnership with a research institute. Crystalline-Silicon-5 increased its symbolic knowledge by keep using the acquired German firms' brand name and the Chinese firms gained access to the synthetic knowledge of the German thin-film producers by keeping the German employees working with R&D.

Acquiring state of the art equipment was crucial for many of the firms to stay competitive in the market. However, essentially everyone had access to the same equipment and technology, so the competitive advantage lied in the know-how of how to use it, rather than just acquiring it, which is why it is not viewed as an important survival mechanism in this study.

6.7 The linkages between the types of upgrading, knowledge bases and upgrading mechanisms

On the next page is *Table 1. How upgrading mechanisms relate to knowledge bases and types of upgrading in the German PV module manufacturing industry* summarising the findings regarding the relationships between upgrading mechanisms, knowledge bases and the types of upgrading found in the German PV module manufacturers industry. Marked in bold are the most important relationships found in the study.

	Product Upgrading	Process Upgrading	Functional Upgrading	Chain Upgrading
Monitoring	**Following product and design developments in the market.** **Facilitates synthetic and symbolic knowledge bases**	**-**	**Maintaining close observation of customers to understand their needs, e.g niche market adaptations** **Facilitates Symbolic and Synthetic Knowledge Bases**	**-**
Mobility	The findings suggest mobility to be of minor importance to the module manufacturers, due to e.g. the strong collaborations within the German industry and place-specific human capital (Fischer et al., 1998) being built up in the companies			
Collaborations	**Formal relationships with Universities and Research Institutes to develop new products and processes** **Facilitates analytical and synthetic knowledge bases** **Informal Relationships with customers to develop design** **Facilitates synthetic and symbolic knowledge bases**	**Mainly informal relationships with suppliers, equipment manufacturers to develop processes further.** **Facilitates synthetic knowledge base**	**Mostly informal relationships with customers (architects, facade builders, distributors and installers) in order to investigate market need and requirements, e.g. full energy solutions** **Facilitates symbolic and synthetic knowledge bases**	-
Internal	**Companies have developed specific technologies, processes and products through many years of experience, which have led to better quality, and durability of the products as well as better production processes.** **Facilitates synthetic knowledge**		-	Many years of experience has allowed companies to offer their own equipment to the market Facilitates synthetic knowledge
Acquiring	Acquiring patent rights in order to add to the technology base Facilitates analytical knowledge	Purchase of state of the art manufacturing equipment in order to improve processes Does not facilitate knowledge bases by itself	Acquisition of other companies in order to increase product portfolio and services. Facilitates all types of knowledge bases	Acquiring other firms in order to move to higher value chain activities. Facilitates all types of knowledge bases

Table 1. How upgrading mechanisms facilitate upgrading of knowledge bases and the types of upgrading in the German PV module manufacturing industry.

7. Conclusion

With increased competition from developing markets, Western manufacturing firms have to increase the skill content of activities or move to market niches, which are protected with entry barriers and are isolated from competition, in order to survive (Humphrey & Schmitz, 2002). This hard lesson was experienced by the German photovoltaic module manufacturers in the beginning of the 2010's, when there was sudden and major over-supply of modules, mainly caused by the Chinese expansion into the market and the following price drop in the module prices. Many German firms went bankrupt during the years to come, but some survived. This paper has investigated the reasons for the survival of German firms by investigating the importance of upgrading mechanisms and their effect on the forms of upgrading and knowledge bases, answering the questions:

- *What upgrading mechanisms are the most important for German PV module manufacturers' survival?*
- *How do upgrading mechanisms facilitate firms' upgrading and knowledge bases?*

The results suggest that, overall, *Collaborations, Monitoring* and *Internal* mechanisms were the most important for the survival of German PV firms, while *Mobility* and *Acquiring* were of less importance. The research shows that the different mechanisms affected the forms of upgrading and knowledge bases in various and different ways as shown in *Table 1.*

Collaborations were shown to facilitate product, process and functional upgrading. Through collaborations with universities and research institutes, firms were able to increase their analytical knowledge base, which in turn facilitated product upgrading. Collaborating with suppliers could increase the synthetic knowledge of the company and lead to process upgrading, while collaborating with customers facilitated symbolic knowledge through design and different product and functional service offerings. The types of collaborations were shown to differ significantly between companies, depending on which type of knowledge base was the most important for them.

Internal mechanisms facilitated product and process upgrading. Through years of experience, companies learned how to use and manipulate the machines, which led to better production processes and products. The long experience of employees meant that a lot of synthetic knowledge was built up over the years, which gave the companies a competitive advantage, since it is hard to transfer synthetic knowledge over large distances. The internal mechanisms led to better quality and durability of the modules, which many customers were willing to pay premium price for.

Monitoring was shown to affect product and functional upgrading. Through monitoring companies realised that functional upgrading by offering full solutions was important for them to compete and subsequently survive. Firms, which, through monitoring, early understood the value for them to engage in niche markets, avoiding the tough competition on the standard module market, also had a better chance to survive. Understanding customer's preferences in design, color etc. increased the firms' symbolic knowledge base and was also largely due to monitoring the market together with informal collaborations.

Mobility and Acquiring have been shown to be important for the upgrading of developing countries' firms, through knowledge transfer from developed countries (van Tuijl et al., 2016). Our findings suggest Mobility and Acquiring not to be of major importance in developed country firms where industry collaboration is high or where firms have too unrelated competences.

Our findings suggest that companies working in solar module manufacturing industry should focus on a *combination of knowledge bases*. Synthetic and analytical knowledge can help to develop better products and processes, through internal mechanisms and collaborations, mainly with universities, research institutes and suppliers, but do not provide the understanding of the needs of the customer. Therefore, companies need symbolic knowledge in combination with analytical and synthetic knowledge to create the highest value product, according to the specifications of the customer. However, the findings also suggest that overall the *synthetic* knowledge base have the strongest impact on the types of upgrading and survival of solar module manufacturing companies.

7.1 Theoretical contributions

Building on works of Martin and Moodysson (2011) and van Tujil et al. (2016), this paper contributes to the upgrading mechanism framework, by extending it and showing the value of using two additional mechanism: *internal* and *acquiring* to the main framework of *mobility, monitoring and collaborations.* According to us, this is a framework which shows great potential to be used in future studies in upgrading literature, as it takes a wider, more detailed perspective of upgrading mechanisms compared to previous studies in the field.

Furthermore, the knowledge base concept has only been used once to show how upgrading can take place via upgrading mechanisms (van Tuijl et al., 2016). The study of van Tuijl et al. (2016) looked at upgrading of synthetic and symbolic knowledge and in a developing country context (van Tuijl et al., 2016), while our case study looks at all three knowledge bases and in a developed country context. We also show the linkages between knowledge bases, upgrading mechanisms and the types of upgrading. To our knowledge this is the first study showing the linkages between all three of these concepts and further incorporating them into a table to show how they are connected. Through the use of a table (*Table 1*), we have shown how researchers can structure the forms of upgrading, knowledge bases and upgrading mechanisms to show how they relate to each other in an innovative way. Using this table researchers can, for example, do comparative studies between companies, industries and countries.

7.2 Managerial implications

The recent crisis in the PV sector is just one in a line of market shakeouts that has occurred throughout industries in modern times. Some companies survive, while others exit the market. This study shows that upgrading mechanisms can greatly affect a company's chances to survive. As the module manufacturing companies in Germany cannot compete on price in the market, they need to innovate to increase value added, i.e. they need to upgrade their activities. Based on the findings, monitoring, collaborations and internal mechanisms can facilitate the necessary upgrading for survival and managers need to be aware of how these mechanisms can facilitate different types of upgrading.

Our research shows that monitoring customers and competitors is crucial for the survival of PV module manufacturing companies. Through monitoring, companies can detect segments in the market not occupied by competitors and develop niche products for this market, which moves them away from the price competition on the standard module market. Monitoring can thus facilitate product upgrading. Furthermore, some downstream activities are best done locally and can bring additional value to the customer. Functional upgrading, in terms of offering the customer additional products and services, is shown in the study to positively affect companies' survival chances and can be utilised by companies when they are unable to compete on price in the market with a standard product.

Collaborating with universities and research institutes should be considered if the company is competing on technology factors and wants to upgrade primarily its analytical knowledge base and upgrade the product, while collaborating with suppliers might be an alternative for companies wishing to increase their synthetic knowledge base and upgrade their processes.

Regarding internal mechanisms, fostering knowledge creation within the firm and knowledge development of the employees was shown to increase the probability of firms' survival. The results suggest that long lasting employees within a firm are great sources of tacit knowledge and play a major role in the incremental upgrading of firms' products and processes, which over time can lead to major innovations. Firms should therefore try to hold on to employees with a lot of place-specific human capital, as this might be lost if the employee leaves the company.

7.3 Future research

The study has found a high importance of functional upgrading such as full solution offering and solar project planning. According to Kaplinsky and Readman (2001) functional upgrading becomes progressively more important as the focus in time shifts away from process and product upgrading. The current theory of dominant design investigates only the importance of Product and Process innovation (Utterback, 1994). However, no studies to this day, to the best of our knowledge, has tried to incorporate functional innovation into the framework. We view this as a very interesting subject and propose that future studies could investigate if and when functional upgrading becomes important within the framework, thus potentially adding a third ”functional innovation” line to the model.

Financing is one of the factors which is important for the survival of the firms, but was not incorporated in this study due to not being connected to upgrading and upgrading mechanisms and thus outside of the scope of this research. However, future research could be done in order to investigate the impact of financial backing and trustworthy investors for companies' survival. Some of the participants (Thin-film-2, Crystalline-Silicon-1, Thin-film-1, Crystalline-Silicon-4 and Research-Institute-2) stated that it is essential to have financial backing and trustworthy investors, who believe in the German PV industry and in the company in order to survive. Even though there were solar module manufacturing companies among the respondents, which did not have any financial support and still survived the crisis, the importance of financial support and trustworthy investors cannot be neglected for survival of manufacturing companies when it no longer can compete on price. This could be investigated thoroughly in future research.

Lastly, as linkages of upgrading mechanisms, knowledge bases and types of upgrading is a new research topic, similar research could be done in other industries, sectors of the value chain and / or in other countries in order to investigate if the same patterns exist in these contexts as were found in this study.

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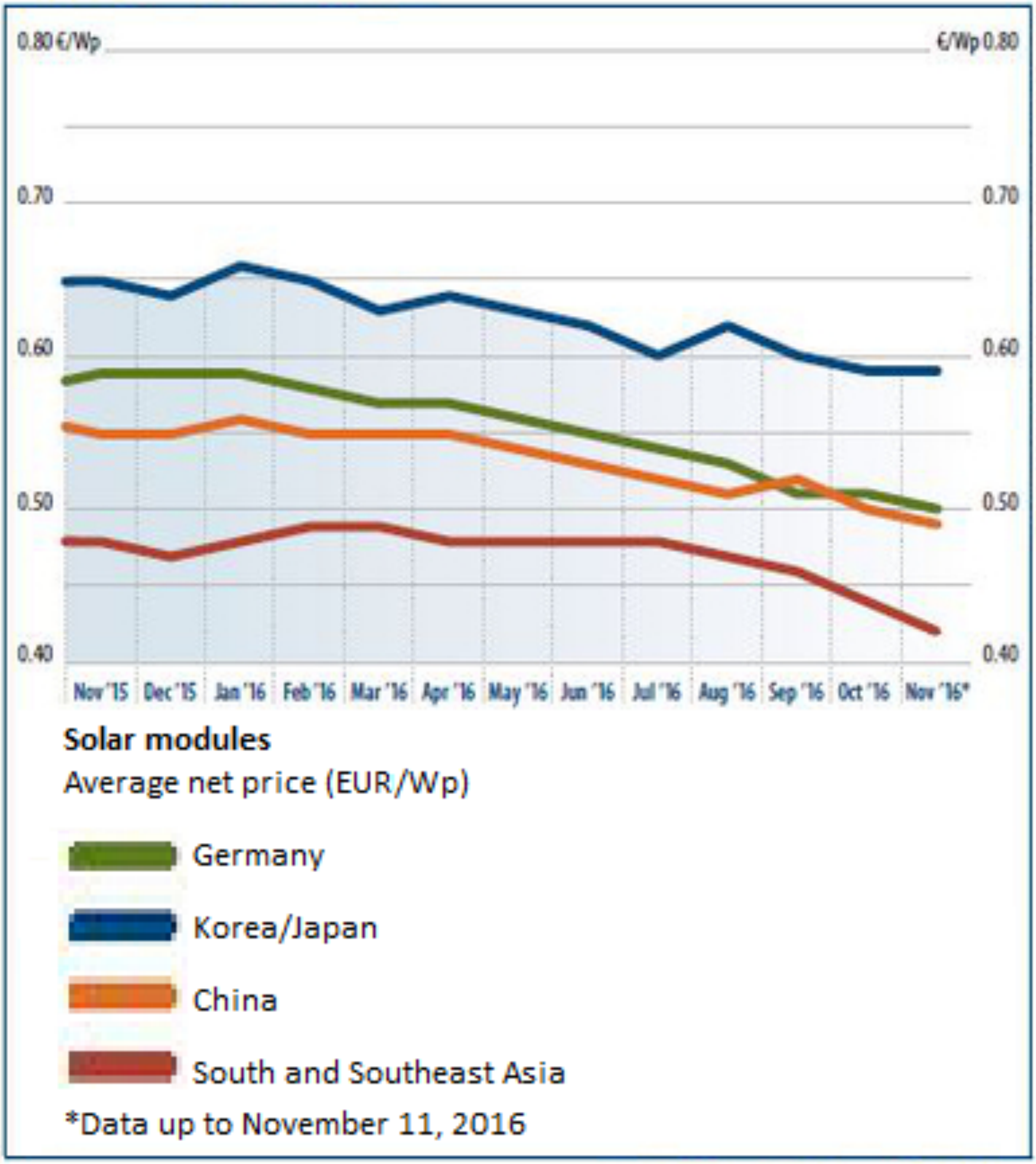
11. Appendix

11.1 Solar module prices



Solar module prices by country
Source: Schachinger, 2016

11.2 Interview guide for companies:

UNIVERSITY OF GOTHENBURG
SCHOOL OF BUSINESS, ECONOMICS AND LAW

Interview Guide

- How can you set yourself apart as a module manufacturer? How do you set yourself apart?
- What are the strongest features of your solar modules compared to modules manufactured by other manufacturers worldwide?
- How have you become successful in this highly competitive industry?
- What are the main reasons for you to be physically present in Germany?

- Do you have any close relationships with other organisations?
    - What type of relationships?
- How important are these relationships for your business?
- Have the relationships changed over the past years?
- What role do you think relationships with other organisations have played in the success of your company?

- How do you work to be innovative?

- What are your thoughts about the future of the German module manufacturing industry?
- What are the main challenges you are facing in the future?

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11.3 Interview guide for institutes:

UNIVERSITY OF GOTHENBURG
SCHOOL OF BUSINESS, ECONOMICS AND LAW

Interview Guide

- Could you tell us briefly about your institute and how it is related to the PV industry in Germany?
- What kind of companies are you cooperating with the most in the German PV industry?
    - Why do you cooperate with these companies?
    - What type of relationships have you established with companies?

- How important are the relationships for your institute and for the companies that you are working with? Why are they important?
- What role do you think linkages with universities and research institutes have played for the successful business development of PV module manufacturing companies? Do you have examples of successful cooperation?
- Have the relationships changed over the past years?

- How innovative do you have to be to compete in the PV module industry?
- According to your opinion, what is the most important success factor for German solar module manufacturing companies?

- What are your thoughts about the future of the German module manufacturing industry?
- What are the main challenges for future German industry growth?
  - What are your main challenges?

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11.4 Interview guide for the silicon supplier

UNIVERSITY OF GOTHENBURG
SCHOOL OF BUSINESS, ECONOMICS AND LAW

Interview Guide

- How can you set yourself apart as a silicon producers? How do you set yourself apart?
- How have you become successful in this highly competitive industry?
- What are the strongest features of your product offering compared to other producers worldwide?

- What are the main reasons for you to be physically present in Germany.
- Why did you choose to start producing silicon in this part of Germany?
- What percentage of your total sales of silicon products do Germany account for?

- How were sales in Germany affected after the 2011 crisis in the PV industry?
- According to you, why are some of the companies in the PV industry in Germany still doing business, while many others have failed?

- What role do you think industry relationships with universities and research institutes have played in the successful development of the PV industry?
- What role do you think relationships between different actors throughout the PV value chain have played in the successful development of the industry?
- Do you have any relationships with universities, research institutes or downstream activities in the PV industry?
    - What type of relationships?
- How important are these relationships for your business?

- What are your thoughts about the future of the German photovoltaic industry?
- What are the main challenges you are facing in the future?

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11.5 Participants of the study

Thin-film module manufacturing companies:

Thin-film-1 - started commercial production of thin-film modules in the late 90's. Since the beginning Thin-film-1 cooperated with different companies and had different owners throughout the years. Since a few years back, the solar module manufacturer is owned by a Chinese company, which helps Thin-film-1 to offer full service starting from glass to module and to the full PV system. Apart from solar module manufacturing in Germany, Thin-film-1 is also working as R&D center for the Chinese owner for thin-film technology and BIPV development.

Thin-film-2 - is one of the main manufacturing companies in Germany of thin-film PV modules and is also a supplier of full turnkey solar PV systems. Moreover, the company is open, in the future, for selling its own thin-film FAB manufacturing solutions and licensing.

Thin-film-3 - is one of the biggest thin-film module manufacturing companies in the world. Thin-film-3 manufactures PV modules and has headquarters established in Germany, however, the main R&D centre is abroad. The company is closely collaborating with a foreign university. The company is also moving towards FAB manufacturing for thin-film solar modules.

Thin-film-4 - is a company with a long lasting history. Apart from vast amount of different business activities, Thin-film-4 is working in the PV industry. The main business of the company is manufacturing FAB production lines for thin-film solar modules. Thin-film-4 is also producing modules throughout innovation lines, however, these lines mainly serve as R&D for FAB equipment testing and module manufacturing is only secondary business activity, primary being FAB manufacturing.

Crystalline silicon manufacturing companies:

Crystalline-Silicon-1 - is focusing on producing top quality and performance PV crystalline silicon modules. Apart from offering various modules, the company is also offering full PV systems together with inverters, wiring and mounting systems. Crystalline-Silicon-1 focuses on private customers and full rooftop solutions. The company is very stable financially and maintained a stable financial position and stable growth throughout the crisis. The company's main focus is on sales, marketing and after sales activities.

Crystalline-Silicon-2 -is a glass-glass crystalline silicon solar module manufacturing company, and according to the company one of the leading companies in quality and operating lifetime.

Crystalline-Silicon-3 - is crystalline silicon module manufacturing company operating since 2008. The company focuses on wide range of PV modules, flexibility, any kind of sizes. The main focus for Crystalline-Silicon-3 is repairs, maintenance and manufacturing of modules for small private customers.

Crystalline-Silicon-4 - is focusing on the maritime niche market, producing and developing solar modules for maritime for more than 20 years and is also working as an OEM.

Crystalline-Silicon-4 is a leader in the maritime market segment and is an independent, stably growing, privately owned company.

Crystalline-Silicon-5 - manufactures solar modules with patented TPO (Thermoplastic Olefin) solution, which allows modules to be fully integrated in the rooftop membrane. This method reduces installation costs, rooftop load and water leakage. Crystalline-Silicon-5 has headquarters in Germany and has a vision of creating efficient and smart applications for solar modules. The company, not originally from Germany, acquired a solar module manufacturing company in Germany in order to strengthen its positions for solar module manufacturing and energy storage systems.

PV research institutes:

Research-Institute-1 - focuses on research of new materials and innovation of devices for PV based on thin-film technology. The institute also develops solar cells for industrial applications and solves different kind of issues to scale up the technology, maintaining close relationships with solar module manufacturing companies.

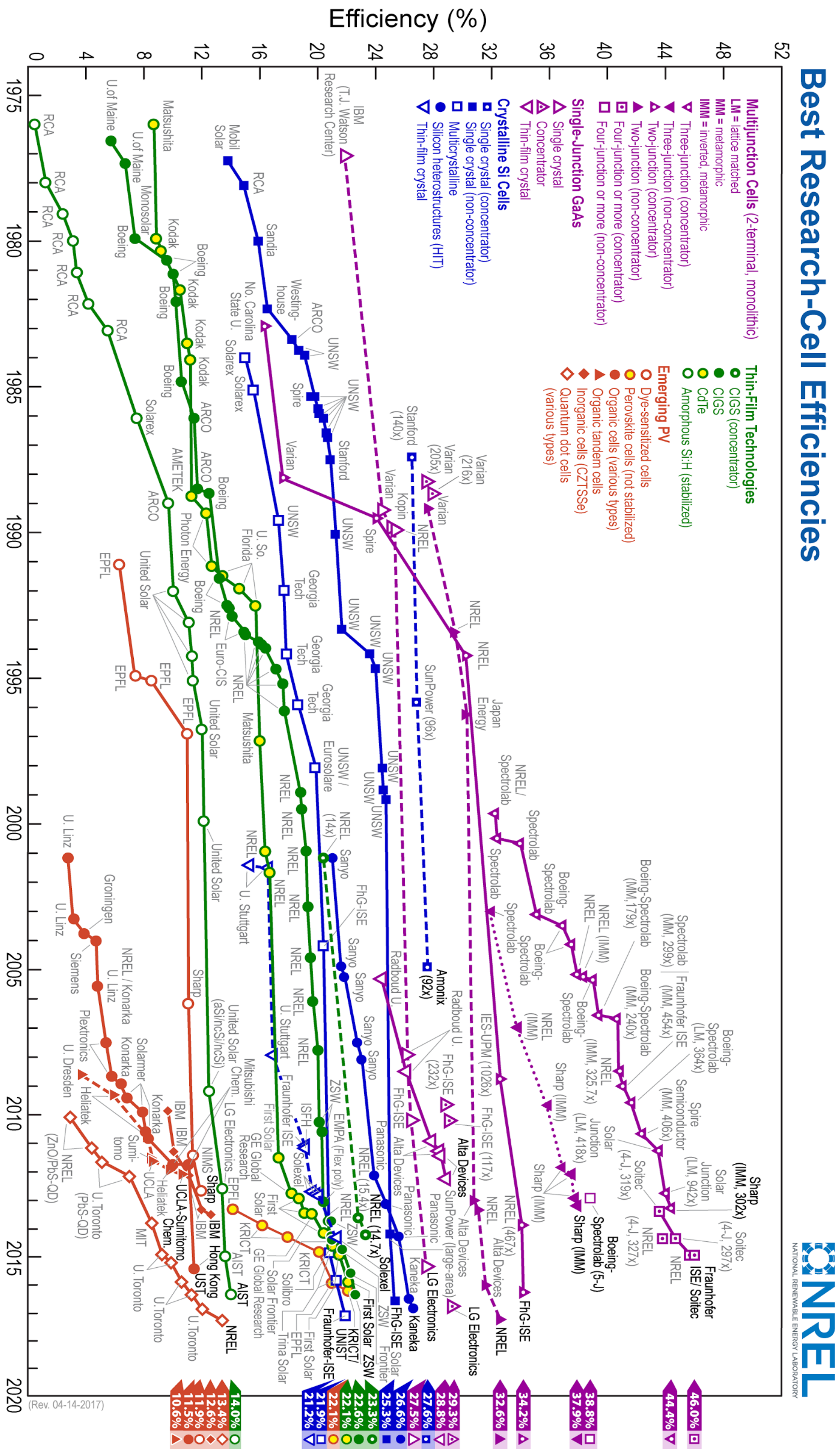
Research-Institute-2 - cooperates with academia and industry in different kind of projects for thin-film PV technology development. The institute has several innovation lines for CIGS and thin-film technologies and helps companies to test scaling up of technology. Research-Institute-2 maintains close collaborations with solar module manufacturing companies across Germany.

Research-Institute-3 - is an institute which does research for applied science and engineering, develops technology for all areas of PV industry, including solar module manufacturing for both crystalline silicon and thin-film technologies.

Silicon supplier:

Silicon-Manufacturer - one of the world’s leaders in polysilicon manufacturing and closely related and familiar with the PV industry.

11.6 Best research-cell efficiencies



Best Research-Cell Efficiencies, Source: NREL, 2017

11.7 Overview of interviews and respondents

Code Name	Type	Respondent's Position in the Company	Method	Date	Place	Duration (In total in hours)
Thin-film-1	Thin-film module manufacturing company	CTO	Face to face interview, recorder was used	March 15th, 2017	Germany	01:10
Thin-film-2	Thin-film module manufacturing company	Head of Marketing, Head of Finance and Head of Research & IP Management	Face to face focus group interview, recorder was used	March 14th, 2017	Germany	00:55
Thin-film-3	Thin-film module manufacturing company	Director CIGS Technology Development	Face to face interview, recorder was not used	March 16th, 2017	Germany	01:00
Thin-film-4	Equipment and thin-film module manufacturing company	Head of Corporate Communications	Phone interview, recorder was used	March 10th, 2017	Gothenburg, Sweden	00:45
Crystalline-Silicon-1	Crystalline Silicon module manufacturing company	Sales and Marketing Director and company representative	Face to face interview, recorder was used	March 15th, 2017	Germany	01:00
Crystalline-Silicon-2	Crystalline Silicon module manufacturing company	CEO	Phone interview, recorder was used	March 9th, 2017	Gothenburg, Sweden	00:55
Crystalline-Silicon-3	Crystalline Silicon module manufacturing company	Production Manager	Face to face interview, recorder was used	March 13th, 2017	Germany	00:45
Crystalline-Silicon-4	Crystalline Silicon module for maritime manufacturing company	CEO	Face to face interview, recorder was used	March 17th, 2017	Germany	01:00
Crystalline-Silicon-5	Crystalline Silicon module manufacturing company	Product Development Manager	Face to face interview, recorder was used	March 14th, 2017	Germany	45:00
Research-Institute-1	Solar research institute	Head of Scientific Coordination and Administration	Face to face interview, recorder was used	March 17th, 2017	Germany	1:10
Research-Institute-2	Solar research institute	Managing Director - Competence Centre Thin-Film- and Nanotechnology for Photovoltaics	Face to face interview, recorder was used	March 13th, 2017	Germany	1:05
Research-Institute-3	Solar research institute	Director Division Photovoltaic Modules, Systems and Reliability	Phone interview, recorder was used	March 9th, 2017	Gothenburg, Sweden	50:00
Silicon-Manufacturer	Silicon supplier	Director Strategic Marketing - Polysilicon	Phone interview, recorder was used	March 8th, 2017	Gothenburg, Sweden	45:00